DEVELOPMENT AND ANALYSIS OF A CVA AND
A 1052 CLASS FAST FRIGATE AIR WAKE MODEL

Ronald L. Nave
Aircraft and Crew Systems Technology Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974

30 September 1978

FINAL REPORT
AIRTASK NO. WF-41-400-000
P. E. No. 62241N

Prepared for
NAVAL AIR SYSTEMS COMMAND
Department of the Navy
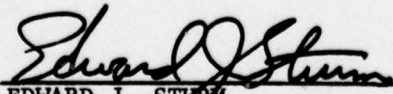Washington, D.C. 20361

DDC
RECEIVED
JUL 25 1979
D

NOTICES

REPORT NUMBERING SYSTEM - The numbering of technical project reports issued by the Naval Air Development Center is arranged for specific identification purposes. Each number consists of the Center acronym, the calendar year in which the number was assigned, the sequence number of the report within the specific calendar year, and the official 2-digit correspondence code of the Command Office or the Functional Directorate responsible for the report. For example: Report No. NADC-78015-20 indicates the fifteeth Center report for the year 1978, and prepared by the Systems Directorate. The numerical codes are as follows:

CODE	OFFICE OR DIRECTORATE
00	Commander, Naval Air Development Center
01	Technical Director, Naval Air Development Center
02	Comptroller
10	Directorate Command Projects
20	Systems Directorate
30	Sensors & Avionics Technology Directorate
40	Communication & Navigation Technology Directorate
50	Software Computer Directorate
60	Aircraft & Crew Systems Technology Directorate
70	Planning Assessment Resources
80	Engineering Support Group

PRODUCT ENDORSEMENT - The discussion or instructions concerning commercial products herein do not constitute an endorsement by the Government nor do they convey or imply the license or right to use such products.

APPROVED BY: _____ DATE: 26 Mar 79

EDWARD J. STURM
By direction

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NADC-78182-60	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* Development and Analysis of a CVA and a 1052 Class Fast Frigate Air Wake Model.		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ronald L. Nave		8. CONTRACT OR GRANT NUMBER(s) AIRTASK WF-41-400-000 P.E. No. 62241N
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aircraft & Crew Systems Technology Directorate Naval Air Development Center Code 6053 Warminster, PA 18974		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS F414PP
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Department of the Navy Washington, DC 20361		12. REPORT DATE 30 September 1978
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*) 102p.		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Ship Air Wake Turbulence Model
Digital Simulation Model
FF1052 Air Wake Simulation
CVA Air Wake Simulation

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Two digital computer programs have been developed in subroutine form to simulate the ship airwake turbulence around a FF1052 Frigate and a CVA. This report documents and analyzes these two models.

DD ,FORM_{JAN 73} 1473   EDITION OF 1 NOV 65 IS OBSOLETE   393 532 UNCLASSIFIED
S/N 0102-LF-014-6601

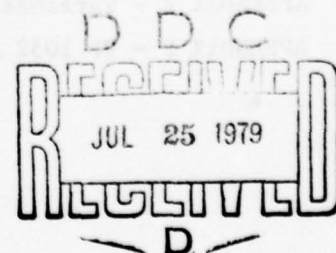SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

S U M M A R Y

This report documents two ship airwake turbulence models which have been developed to aid in the analysis and simulation of the shipboard launch and recovery dynamics of conventional and VSTOL aircraft. The two computer subroutines represent a large deck carrier and a FF 1052 frigate air wake. The carrier model has been used extensively for automatic carrier landing simulations. The frigate airwake model has been developed more recently and has not been widely tested. The FF 1052 airwake model has been installed as part of the NAVAIRDEVCEN VSTOL Launch and Recovery Program described in reference (a). The model has been analytically validated against wind tunnel data, but it has not been tested in a piloted simulator.

These two models are being documented in the hope that they may form the basis for a standardized method of simulating turbulence for shipboard launch and recovery analysis.

Accession For

NTIS GRA&I	
DDC TAB	
Unannounced	
Justification	

By_____

Distribution/

Availability Codes

Dist	Avail and/or special
A	

D D C
RECEIVED
JUL 25 1979
D.

T A B L E   O F   C O N T E N T S

L I S T   O F   T A B L E S

L I S T O F F I G U R E S

L I S T   O F   F I G U R E S   (Continued)

INTRODUCTION

Two turbulence model algorithms have been developed for use in the design and analysis of conventional and vertical take-off aircraft. These are an attack carrier model (CVA) and a FF 1052 frigate model. The CVA model has been used since 1971 in the simulation of manual and automatic landings aboard large deck carriers. This model has been used at the NASA Ames Research Simulation Facility in piloted simulations of the F-14, A-7, and EA-6B aircraft. References (b) and (c) describe the data and equations used to develop the model. Free air turbulence, steady, and unsteady burble components are combined to produce the complete CVA model. To make the algorithm more suitable for VSTOL aircraft, several changes have been made from the form described in reference (c). These are as follows:

1. The ship airwake velocity components are programmed to exponentially decrease in magnitude beyond specified bounds of altitude and lateral position.

2. The vertical component of the steady air wake has been changed to include an upwash near the bow. This was inferred from time histories of AV8A launches aboard the U.S.S. Roosevelt. (See figure 1.)

3. An option to provide discrete gust sinusoids in place of the ship air wake model has been added. These inputs follow the form described in reference (f).

The model is limited to cases where the wind is aligned with the landing deck. Wind velocity is specified by setting the ship speed variable, VS.

The second model has been developed exclusively for VSTOL aircraft and is intended to represent wind conditions near an FF 1052 frigate.

The turbulence algorithm was developed from data derived from the wind tunnel test of a 1/50 scale FF 1052 ship model. These data are contained in reference (d). The structure for the algorithm was based on work performed by the Vought Corporation and described in reference (e). However, the model described herein has been modified from the original format as a result of additional analysis of the data contained in reference (d). The model described herein is a somewhat refined version of the Vought model.

This model was programmed on the NAVAIRDEVCEN CDC 6600 computer. The Fortran listings included in this report represent the present status of the two models.

The subroutines have been tested in batch mode runs and are considered to be reasonably accurate. However, the author takes responsibility for any deficiencies that may still remain in the code.

The FF 1052 air wake model was examined by computing time histories, power spectra, and probability distributions and then comparing these with the wind tunnel velocity time histories.

This report describes all work done to validate and adjust the FF1052 model to agree with wind tunnel data. Both the CVA model and the FF1052 model are offered for inspection, use, and criticism.
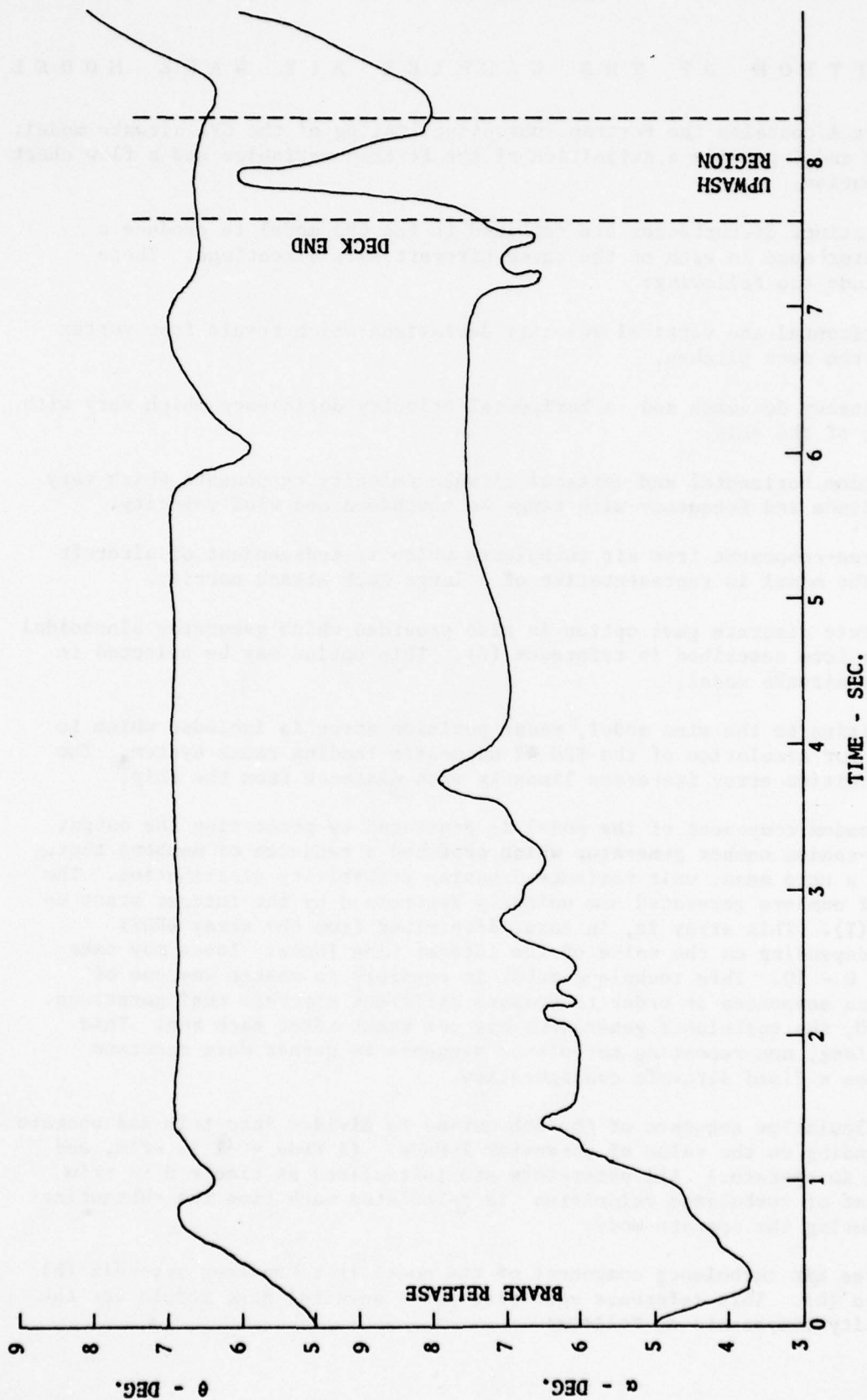
Figure 1 - Pitch Attitude and Angle of Attack During STO Launch

DESCRIPTION OF THE CARRIER AIR WAKE MODEL

Appendix A contains the Fortran subroutine listing of the CVA airwake model. Appendices B and C provide a definition of the Fortran variables and a flow chart of the subroutine.

Four distinct disturbances are combined in the CVA model to produce a velocity disturbance in each of the three aircraft axis directions. These sources include the following:

1. Horizontal and vertical velocity deviations which result from vortex shedding as the deck pitches.

2. A steady downwash and a horizontal velocity deficiency which vary with distance aft of the ship.

3. Random horizontal and vertical airwake velocity components which vary in RMS amplitude and frequency with range to touchdown and wind velocity.

4. Three-component free air turbulence which is independent of aircraft position. The model is representative of a large deck attack carrier.

A separate discrete gust option is also provided which generates sinusoidal gusts of the form described in reference (f). This option may be selected in place of the airwake model.

In addition to the wind model, radar position error is included which is appropriate for simulation of the SPN-42 automatic landing radar system. The simulated position error increases linearly with distance from the ship.

Each random component of the model is generated by processing the output of a pseudo-random number generator which produces a sequence of numbers that approximate a zero mean, unit variance Gaussian probability distribution. The sequences of numbers generated are uniquely determined by the integer start up array IRDST(I). This array is, in turn, determined from the array IRDSI (I, Ionce) depending on the value of the integer flag Ionce. Ionce may take values from 0 - 10. This technique makes it possible to repeat any one of 10 turbulence sequences in order to compare different aircraft configurations. If Ionce = 0, the turbulence generators are not reset after each run. This produces a long, non-repeating turbulence sequence to gather more accurate statistics on a fixed aircraft configuration.

The calculation sequence of the subroutine is divided into trim and operate modes depending on the value of parameter I Mode. (I Mode = -1 in trim, and I Mode = +1 in operate.) All parameters are initialized at time = 0 in trim and a new set of turbulence velocities is calculated each time the subroutine is called during the operate mode.

The free air turbulence component of the model is taken from appendix (b) of reference (h). This reference specifies power spectral gust models for the three velocity components as follows:

$$\phi \frac{\Delta u}{v_0} = \frac{200/v_0{}^3}{\left(\frac{S}{v_0/100} + 1\right)\left(\frac{-S}{v_0/100} + 1\right)} \frac{(\text{ft/sec})^2}{(\text{rad/sec})}$$

$$\phi \frac{\Delta v}{v_0} = \frac{\left(\frac{5900}{v_0{}^3}\right)\left(\frac{S}{v_0/400} + 1\right)\left(\frac{-S}{v_0/400} + 1\right)}{\left(\frac{S}{v_0/1000} + 1\right)\left(\frac{-S}{v_0/1000} + 1\right)\left(\frac{S}{3v_0/400} + 1\right)\left(\frac{-S}{3v_0/400} + 1\right)} \frac{(\text{ft/sec})^2}{(\text{rad/sec})}$$

$$\phi \frac{\Delta w}{v_0} = \frac{71.6/v_0{}^3}{\left(\frac{S}{v_0/100} + 1\right)\left(\frac{-S}{v_0/100} + 1\right)} \frac{(\text{ft/sec})^2}{(\text{rad/sec})}$$

The corresponding root-mean-square gust amplitudes are:

u_G = .76 M./sec (2.5 ft/sec)

w_G = .457 M./sec (1.5 ft/sec)

v_G = .728 M./sec (2.39 ft/sec)

The frequency parameters of the free air turbulence filters are determined by the trim airspeed v_0. Since the algorithm was developed for conventional flight simulation, the equations do not permit the direct substitution of zero airspeed for a hover case. For low trim speeds, the parameter is arbitrarily set to 18.29 M./sec (60 ft/sec). This value was selected as a reasonable estimate of the maximum relative wind over a moving ship.

The turbulence routine options are determined by selecting integer flag parameters as either 0 or 1. The normal values of these flags are as follows:

Iwind = 1

ILburb = 1

ILturb = 1

IBfrz = 0

Idisct = 0

Iubt = 0

Ivbt = 0

Iwbt = 0

This produces a complete ship airwake model for approach simulation. The complementary values produce these effects:

Iwind = 0   Return all zero turbulence values.

ILburb = 0   Select alternate downwash function.

ILturb = 0   Set all free air turbulence components to zero.

IBfrz = 1   Fix turbulence range variable to xd = xfrz.

Iubt = 1   Set u component of airwake burble to zero.

Ivbt = 1   Set v component of airwake burble to zero.

Iwbt = 1   Set w component of airwake burble to zero.

Idisct = 1   Select discrete gust options in place of carrier airwake model.

The ship dependent portion of the airwake was developed primarily from water tunnel tests of CVA ship models. The steady components consist of tabulated values of horizontal and vertical velocity functions ($\Delta u/vs$ and $\Delta w/vs$) versus range. These functions are shown in figure 2. The downwash and reduction in relative wind is determined by multiplying the tabulated functions by ship speed vs. The model assumes that all the wind is generated by the ship and that the velocity is aligned with the landing deck.

Periodic wind components with magnitudes proportional to ship pitch are also included. These sinusoidal vertical and horizontal components propagate aft from the ship at 85 percent of the ship speed and decay in amplitude with range.

The apparent frequency at which the velocity varies is determined by the aircraft closing speed according to formula

$$\text{Magnitude} = \text{cosine}\left[\omega_p\left(1. + \frac{\Delta v}{0.85 \cdot v_s}\right) \cdot t + \frac{x_d}{0.85 \cdot v_s} + \phi - 1.57\right]$$

where ω_p = ship frequency, Δv = aircraft closing rate, v_s = ship speed, x_d = distance to ship cg, and ϕ = phase.

The magnitude of the sinusoid decreases linearly with distance aft of the ship. The burble is set to zero outside of established limits fore and aft of the ship. Additional limits on magnitude are established by altitude and lateral position of the aircraft. The magnitude is assumed to decrease exponentially at distances greater than 100 feet to the left or right of the ship and at altitudes greater than 50 feet above the deck. Reference (i) indicates that the burble is largely restricted to this region.
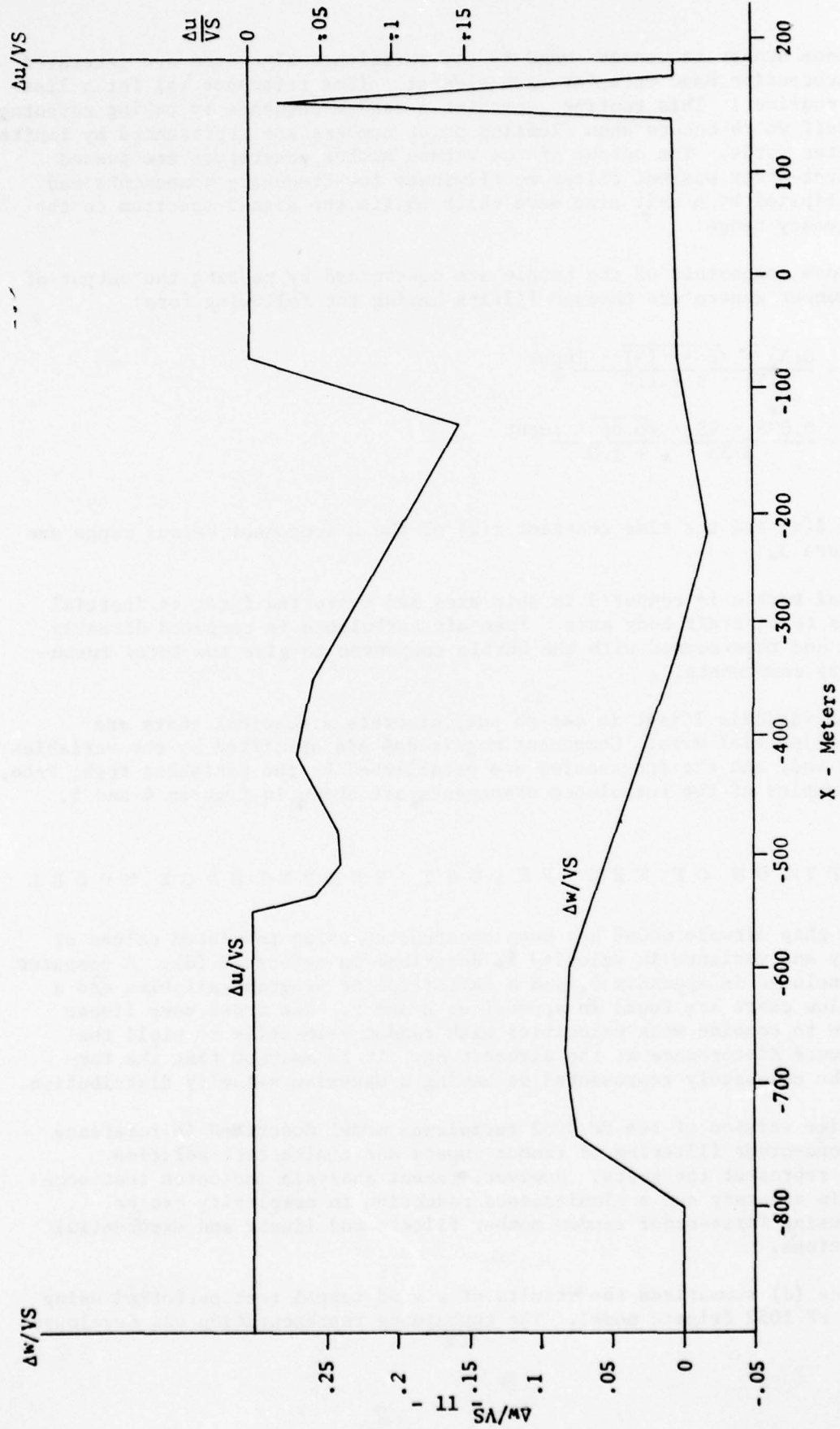
Figure 2 - CVA Ship Burble Steady Wind Ratios

The random number sequences used by the turbulence algorithm are generated by calling subroutine Rand once for each element. (See reference (a) for a listing of this routine.) This routine generates a random sequence by taking advantage of the roundoff which occurs when floating point numbers are represented by finite length computer words. The output of the random number generators are passed through a first-order washout filter to eliminate low-frequency components and are then multiplied by a unit sine wave which shifts the signal spectrum to the desired frequency range.

The random components of the burble are determined by passing the output of the random number generators through filters having the following form:

$$ub2(s) = \frac{\delta(X) \cdot \sqrt{2 \cdot \tau(X)} \cdot \text{Input}}{\tau(X) \cdot s + 1.0}$$

$$wb2(s) = \frac{0.035 \cdot VS \cdot \sqrt{6.66} \cdot \text{Input}}{3.33 \cdot s + 1.0}$$

The variance $\delta(x)$ and the time constant $\tau(x)$ of the u component versus range are shown on figure 3.

The total burble is computed in ship axes and converted first to inertial axes and then to aircraft body axes. Free air turbulence is computed directly in body axes and then summed with the burble component to give the total turbulence velocity components.

When the variable Idisct is set to one, discrete sinusoidal gusts are calculated in inertial axes. Component magnitudes are specified by the variables Vmn, Vme and Vmd, and the frequencies are established by the variables Frth, Frte, and Frtd. Samples of the turbulence components are shown in figures 4 and 5.

DESCRIPTION OF THE FF1052 TURBULENCE MODEL

A small ship airwake model has been constructed using tabulated values of mean velocity and variance in velocity as described in reference (d). A computer listing is included in appendix D, and a definition of program variables and a subroutine flow chart are found in appendices E and F. The model uses linear superposition to combine mean velocities with random velocities to yield the total turbulence disturbance at the aircraft cg. It is assumed that the turbulence may be adequately represented as having a Gaussian velocity distribution.

An earlier version of the FF 1052 turbulence model described in reference (e) used second-order filtering of random inputs and cosine extrapolation functions to represent the gusts. However, recent analysis indicates that some improvement in accuracy and a simultaneous reduction in complexity can be achieved by using first-order random number filters and linear and exponential shaping functions.

Reference (d) summarizes the results of a wind tunnel test performed using a 1/50 scale FF 1052 frigate model. The turbulence representation was developed
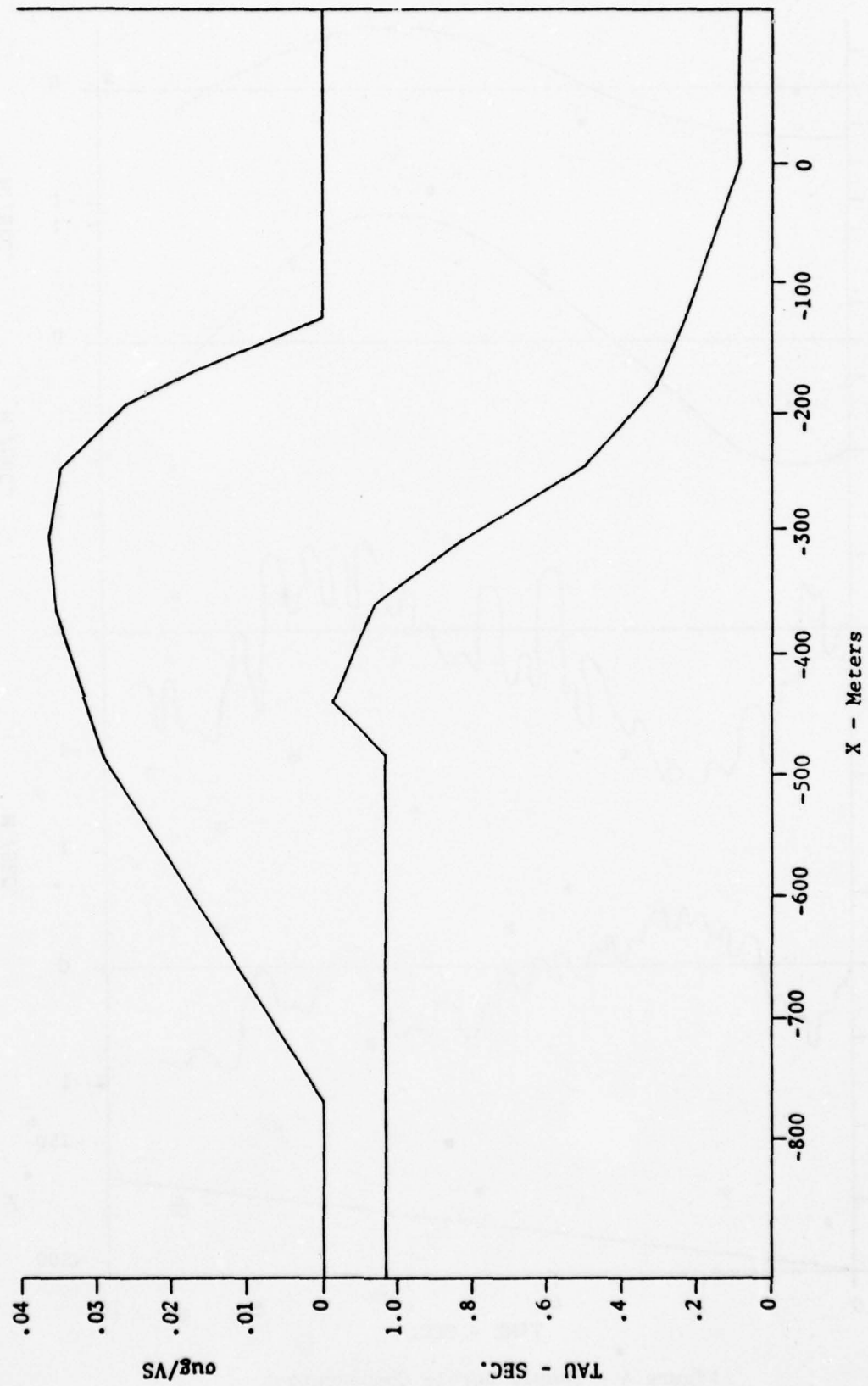
Figure 3 - U Component Burble Time Constant and Variance
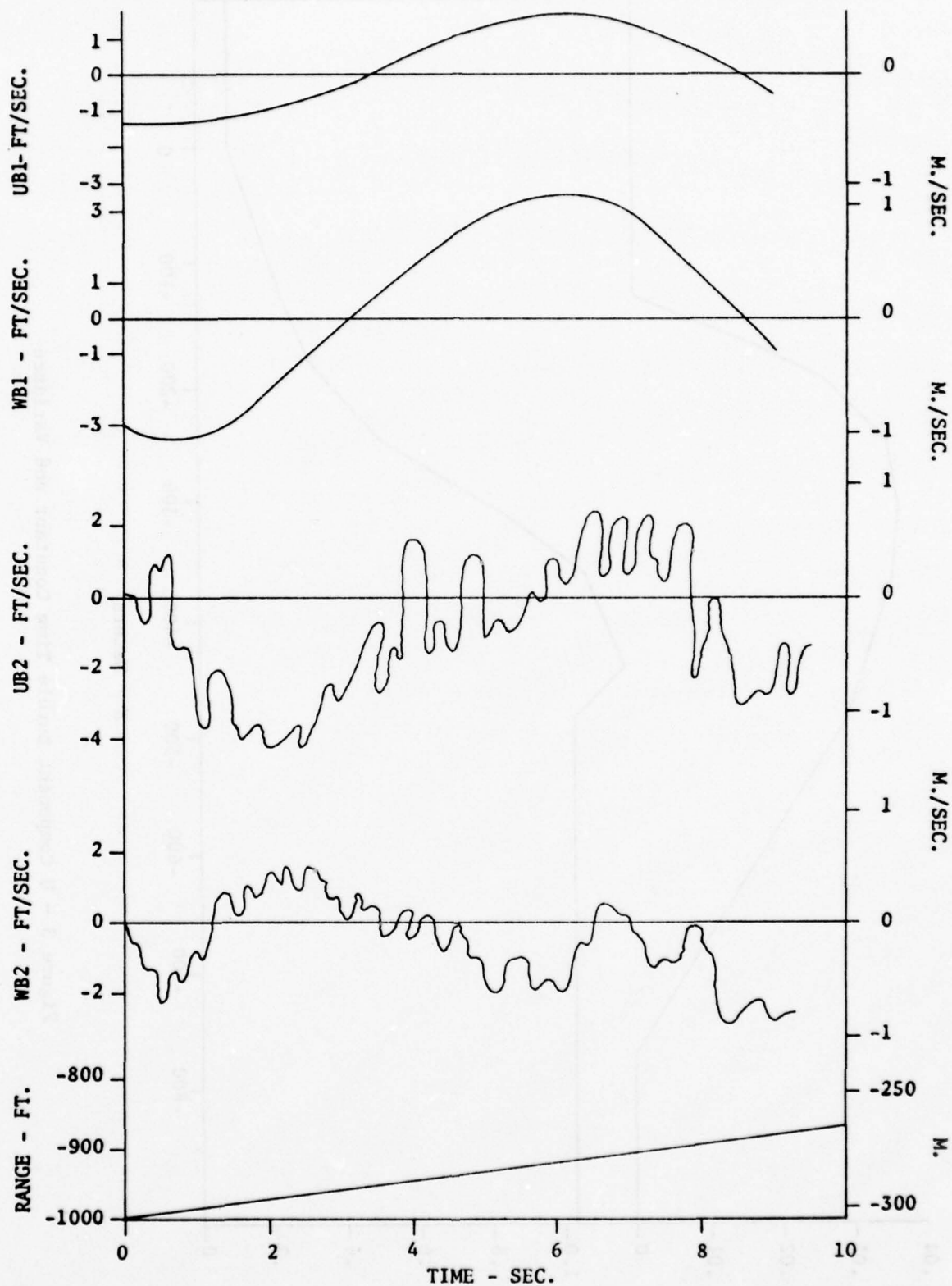
Figure 4 – Sample Burble Components
VO = VS = 18 M./Sec. (60 Ft./Sec.)
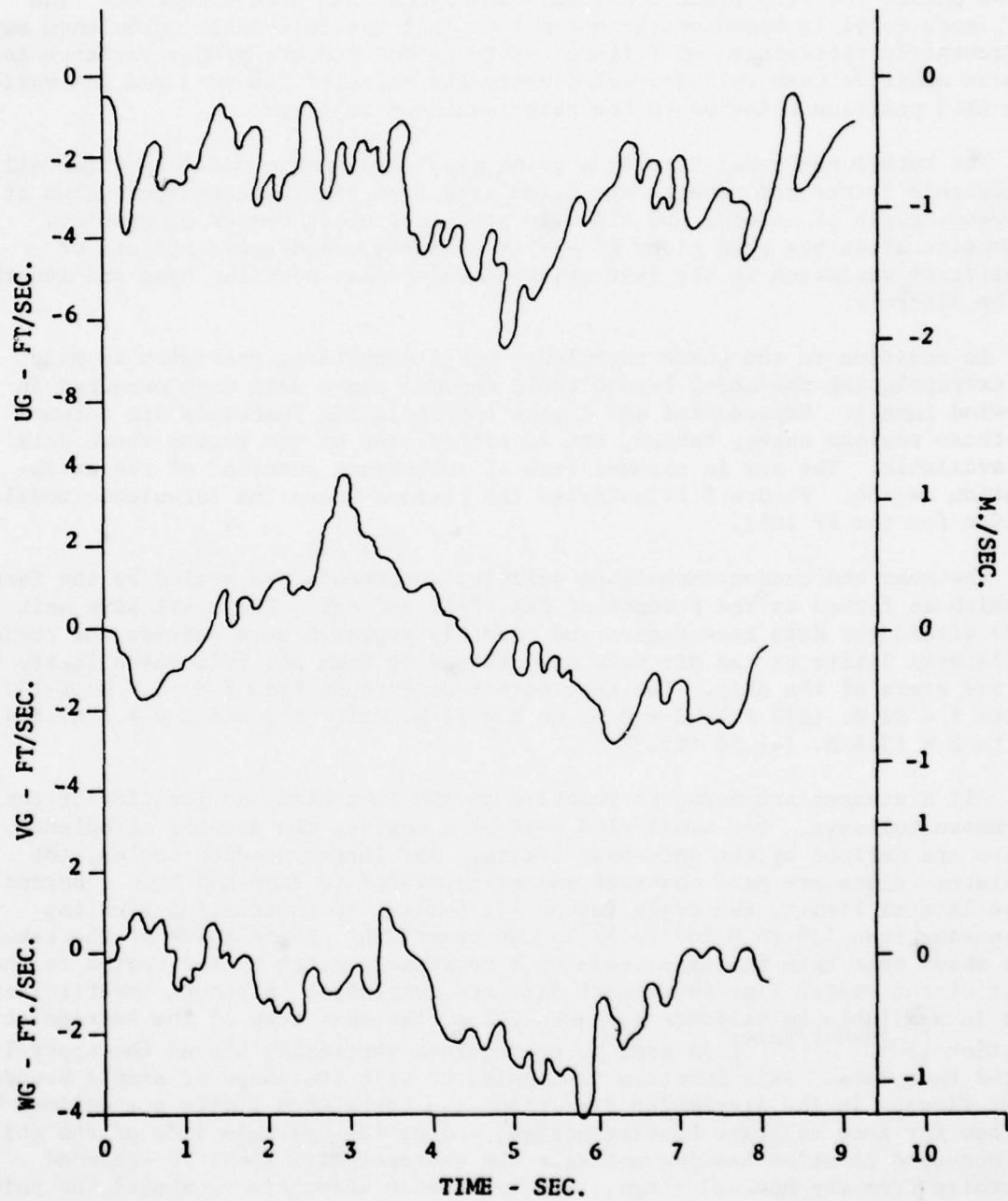
Figure 5 - Sample of CVA Simulated Free Air Turbulence

from statistical summaries of the measured turbulence velocities which define the mean and variance of the three velocity components recorded by an array of hot wire anenometer probes placed downstream of the ship model. The mean and variance were computed from a series of 262 measurements made over a 1.6-second period for each probe location, wind speed, and wind direction. The turbulence model is based on the assumption that the full-scale turbulence may be accurately represented as filtered white noise with the proper variance and with an additive mean velocity value where the value of the mean and the varian vary with position relative to the ship touchdown bullseye.

The turbulence model assumes a point mass aerodynamic model in which all aerodynamic forces and moments are calculated from the instantaneous value of airspeed, angle of attack, and sideslip at the aircraft center of gravity. No consideration has been given to either unsteady aerodynamic effects or significant variation in the instantaneous velocities over the span and length of the aircraft.

In addition to the basic turbulence model structure, provision is made for extrapolating the model beyond those regions where data were measured in the wind tunnel. Exponential and linear extrapolation functions are assumed for those regions above, behind, and to either side of the region where data are available. The air is assumed free of turbulence outside of the extrapolation region. Figure 6 illustrates the regions where the turbulence model applies for the FF 1052.

The mean and random turbulence velocity components are scaled by the factor $F1$ which is formed as the product of $Fx1$, $Fy1$, and $Fz1$. These all have unit value within the data base region and smoothly approach zero outside the region. The lateral limits of the air wake are defined by Ymax and Ymin which locate the bow and stern of the ship. The test data base extends from $Y = -5.7$ M. (-18.75 ft) to $Y = 52$ M. (170 ft), $X = 0$ M. to $X = 76$ M. (250 ft), and $Z = 4.4$ M. (14.58 ft) to $Z = 13.6$ M. (44.58 ft).

All distances are measured relative to the instantaneous location of the touchdown bullseye. For small wind over deck angles, the lateral turbulence limits are defined by the data base limits. For larger heading angles, the tabulated values are held constant and extrapolated to Ymax and Ymin. Beyond these lateral limits, the scale factor $Fy1$ follows an exponential function decreasing from 1.0 to 0.367 (e^{-1}) in one beamwidth. Examination of the tabulat data shows that this function produces a reasonable match in the region to the right of the center line where most data are available. Although insufficient data is available to validate the assumption, the same form of the extrapolating function $\left(e^{-(H-Ho)/Beam}\right)$ is used to extrapolate vertically beyond the upper limi of the test data. This function is consistent with the shape of simple boundary layer flows. In the streamwise direction, the turbulence limits are defined by the bow for zero relative heading angles, and by the upstream side of the ship for non-zero relative heading angles. The extrapolation limit is extended laterally from the bow and stern. All turbulence velocities computed for points in front of this line are diminished by the X extrapolation function $Fx1$ which decays exponentially. A linearly scaled extrapolation function is used for $Fx1$ aft of the data base limit of 76 M. (250 feet).
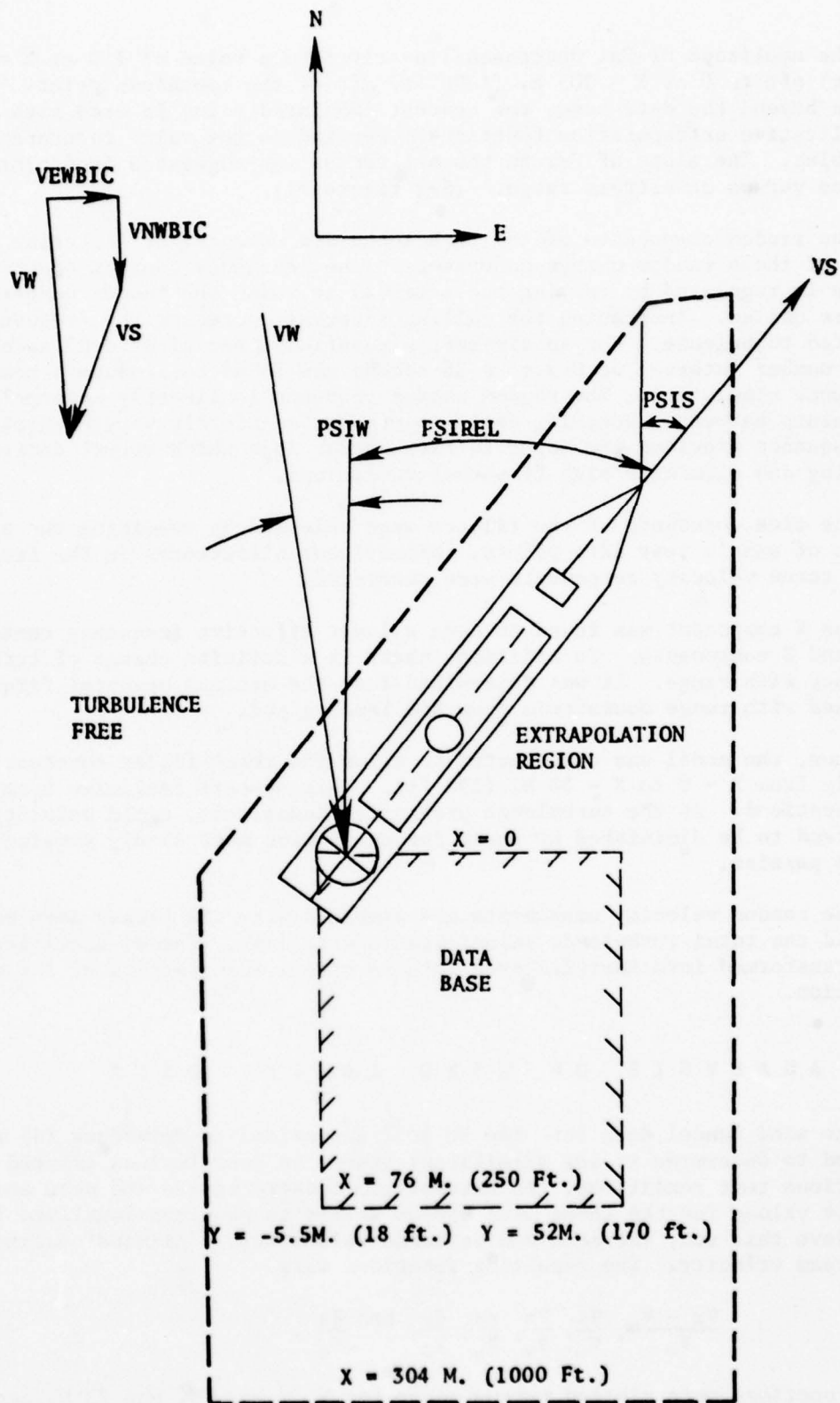
Figure 6 - FF 1052 Ship Airwake Model Geometry

The amplitude of Fxl decreases linearly from a value of 1.0 at X = 76 M. (250 ft) aft to 0 at X = 305 M. (1000 ft) aft of the touchdown point. In the regions beyond the data base, the nearest tabulated value is used with the multiplicative extrapolation function Fl applied to the value returned from the tables. The slope of Fxl in the aft region was suggested from plots of variance versus downstream range. (See figure 7.)

The random components of the turbulence are produced by filtering the output of these random number generators. The frequency content of the turbulence is regulated by varying the interval at which the random number generators are called. Increasing the calling interval decreases the frequency of the simulated turbulence. For an aircraft simulation interval of 0.05 second, a random number interval of 0.3 to 0.35 second was found to produce a reasonable turbulence simulation. The random number sequence is linearly interpolated for time values between succeeding calls to produce a smoothly varying number sequence. This sequence provides the input to first-order lags which effect additional filtering and eliminate high frequency variations.

The time constants of the filters were selected by examining the power spectra of sample test data points. Significant differences in the frequencies of the three velocity components were uncovered.

The X component was found to have a lower effective frequency content than the Y and Z components. In addition, there is a definite change of turbulence frequency with range. It was determined that the maximum spectral frequency decreased with range downstream from the landing pad.

Thus, the model was constructed to allow the three filter constants to vary linearly from X = 0 to X = 58 M. (190 ft). This appears realistic from physical considerations. As the turbulence propagates downstream, rapid velocity fluctuations tend to be diminished by shear forces whereas more slowly varying velocities tend to persist.

The random velocity components are combined with the steady mean components to yield the total turbulence velocities in wind axes. These velocities are then transformed into inertial axes for use by the main portion of the aircraft simulation.

ANALYSIS OF WIND TUNNEL DATA

The wind tunnel data for the FF 1052 summarized in reference (d) were analyzed to determine if any significant trends or correlations existed among the various test conditions. An attempt was made to reduce the mean and variance values for the three wind speeds tested to nondimensionalized functions. To achieve this end, the mean and variance values were nondimensionalized by the freestream velocity. The resulting functions were

$$\frac{Vx - V_\infty}{V_\infty}, \frac{Vy}{V_\infty}, \frac{Vz}{V_\infty}, \frac{\delta x}{V_\infty}, \frac{\delta y}{V_\infty}, \text{ and } \frac{\delta z}{V_\infty}.$$

These functions were plotted versus range for V_∞ = 10, 18, and 23 M./sec.
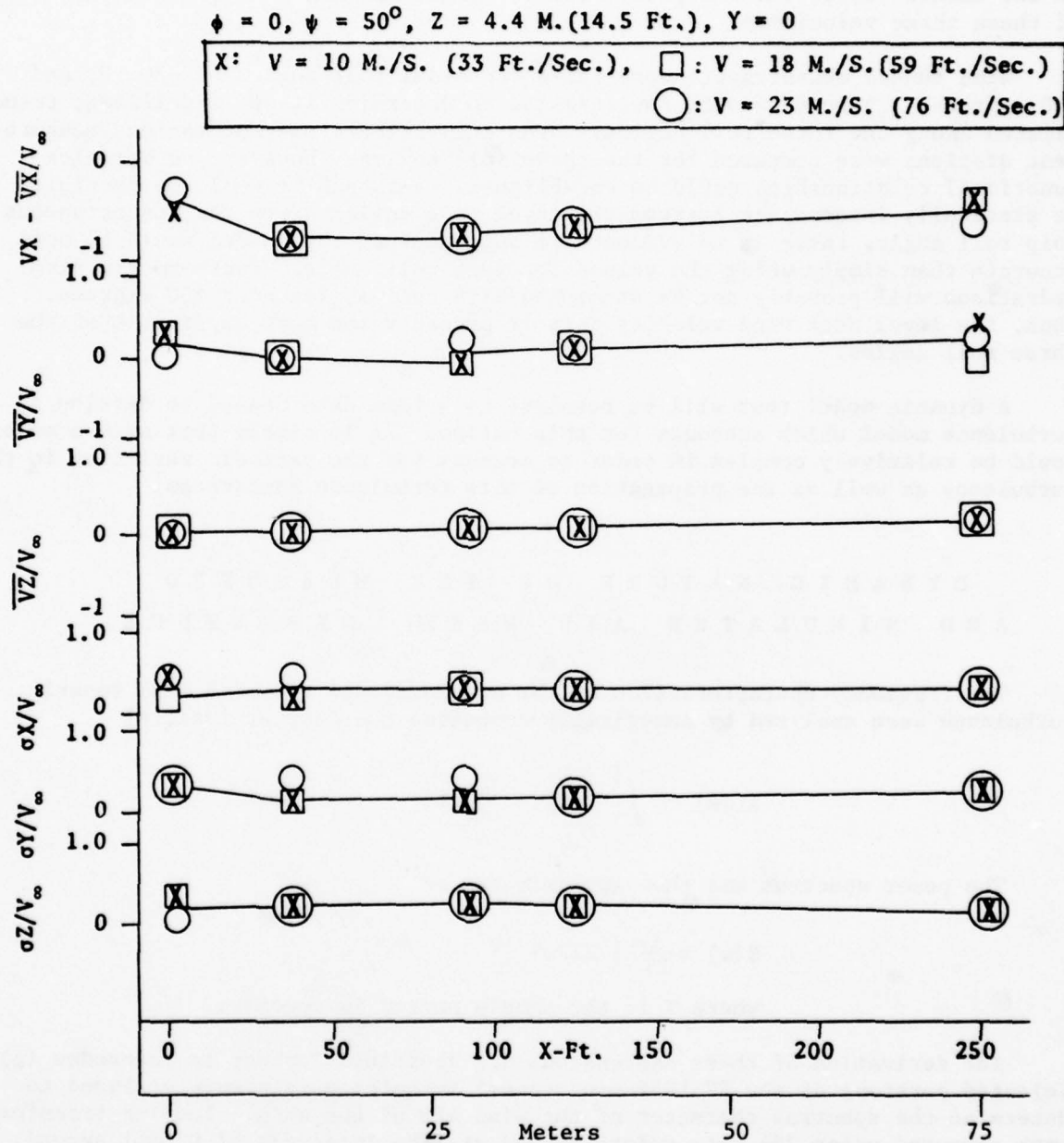
Figure 7 - Nondimensionalized Turbulence Parameters Versus Range

Figure 7 illustrates these functions. It can be seen that the nondimensionalized functions for the three velocities agree rather well. This suggests that a generalized model could be used which would be valid for all relative wind velocities. However, the present model is restricted to the three freestream velocities used in the tunnel tests, and a separate set of nonlinear tables is required for each of these three velocities.

Wind tunnel measurements were taken for model roll angles of -30, 0, and +30 degrees. These data were investigated to determine if any significant trends existed among the three roll angles. Mean and variance size at various measurement stations were compared for the three roll angles. However, no definite functional relationships could be established. Although it would be possible to statically interpolate between the three roll angles given the instantaneous ship roll angle, there is no evidence to suggest that this model would be more accurate than simply using the values for zero roll angle. Furthermore, air operations will probably not be attempted with roll angles near ±30 degrees. Thus, the level deck wind velocity data is probably the most applicable of the three roll angles.

A dynamic model test will be required to obtain data needed to develop a turbulence model which accounts for ship motion. It is likely that such a model would be relatively complex in order to account for the periodic variation in the turbulence as well as the propagation of this turbulence downstream.

DYNAMIC NATURE OF THE MEASURED AND SIMULATED AIR WAKE TURBULENCE

The frequency characteristics of the simulated and measured wind tunnel turbulence were analyzed by numerically computing the Fourier integral

$$X(J\omega) = \int_0^T X(t)\ e^{-J\omega t}dt.$$

The power spectrum was then approximated as

$$S(\omega) \approx \frac{1}{2T}\ |\ X(J\omega)\ |^2$$

where T is the sample period in seconds.

The derivation of these expressions are described further in reference (g). Selected portions of the FF 1052 wind tunnel turbulence data were analyzed to determine the spectral character of the wind aft of the ship. Fourier transforms were computed using 256 data points spaced at time intervals of 0.0061 second. A fast Fourier transform routine was used to compute the spectra from 0 to 515 rad/sec. model scale. The transform was calculated with

$$\Delta\omega = \frac{2 \cdot PI}{Nsamples}\ \text{rad./sec. and}$$

$$\text{maximum frequency} = \frac{PI}{\Delta T} = 515\ \text{rad./sec.}$$

TABLE I

Selected Wind Tunnel Test Points Used in Spectral Analysis

Yaw (deg.)	Roll (deg.)	Speed (M/S)	X (Meters)	Y (Meters)	Z (Meters)
30	0	9	0	0	4.2
50		9		0	4.2
50		9		0	7.6
0		16		5.5	4.2
0		16		0	4.2
0		16		0	7.6
30		16		5.5	4.2
30		16		0	4.2
30		16		0	7.6
50		16		0	4.2
50		16		0	7.6
0		22		5.5	4.2
30		22	0	0	4.2
30		9	11		4.2
30		9			7.6
50		9			4.2
50		9			7.6
30		16			7.6
30		23	11		4.2
30		10	27		4.2
30	0	18	27	0	4.2

TABLE II

Statistics of Frequency Value Corresponding to Maximum of Spectra Grouped by Velocity and Velocity Component

Freestream Velocity			Frequency – Rad/Sec.			
M./S.	(ft/sec)	Component	Average	Maximum	Minimum	RMS
9.1	30	X	60	110	30	30
9.1	30	Y	76	110	10	34
9.1	30	Z	90	150	30	43
16.46	54	X	95	190	10	52
16.46	54	Y	108	260	10	99
16.46	54	Z	140	290	30	90
21.9	72	X	90	170	30	58
21.9	72	Y	130	170	70	43
21.9	72	Z	290	410	150	107

TABLE III

Statistics of Peak Spectral Velocity Grouped by Velocity Only

Velocity		Peak Spectral Frequency – Rad/Sec.			
M./S.	(Ft./Sec.)	Average	Maximum	Minimum	RMS
9.1	(30)	75	150	30	45
16.46	(54)	114	290	15	80
21.9	(72)	170	410	30	114

Because the number of samples was relatively small, the power spectra were generally very erratic. The data were thus smoothed by averaging over groups of six succeeding frequency points. Figures 8 to 10 illustrate samples of the smoothed spectral data. The sample cases shown in table I were examined with regard to spectral content.

These data were analyzed to determine if any significant trends existed with respect to the spectral distributions. The frequency at which the spectrum attained its maximum value was computed for each case and the data were sorted according to freestream velocity and velocity component. The maximum, minimum, average, and RMS value of the frequency at which the peak of the spectrum occurs is tabulated in table II.

Grouping the data by freestream velocity only, the frequency statistics can be summarized as shown in table III.

Figure 11 summarizes the frequency trend as a function of test condition velocity. A least squares fit of the three gross averaged frequencies yields the relation

$$\omega \, {}^{max}_{test} = 3.837 + 2.2274 \cdot V - \text{rad/sec.}$$

Strouhal scaling based on model length is used to obtain the equivalent full-scale frequency as

$$\omega \, {}^{max}_{full \; scale} = 0.07674 + 0.04548 \cdot V - \text{rad/sec.}$$

For the test velocities, this becomes

TABLE IV

Turbulence Frequency Versus Airspeed

ω – Full Scale	V – Ft./Sec.
1.440	30
2.76	59
3.53	76

This differs from the second-order filter model frequency of 1.9 rad./sec. at V = 18 M./S. (59 ft./sec.) as described in reference (d). If additional wind tunnel data is unavailable, the FF 1052 model may be applied to larger or smaller ships having similar geometry or the same ship at different velocities by applying Strouhal scaling, where

$$SN = \frac{f \cdot h}{V}$$

SN = Strouhal number
f = Turbulence frequency
h = Ship beam
V = Flow velocity
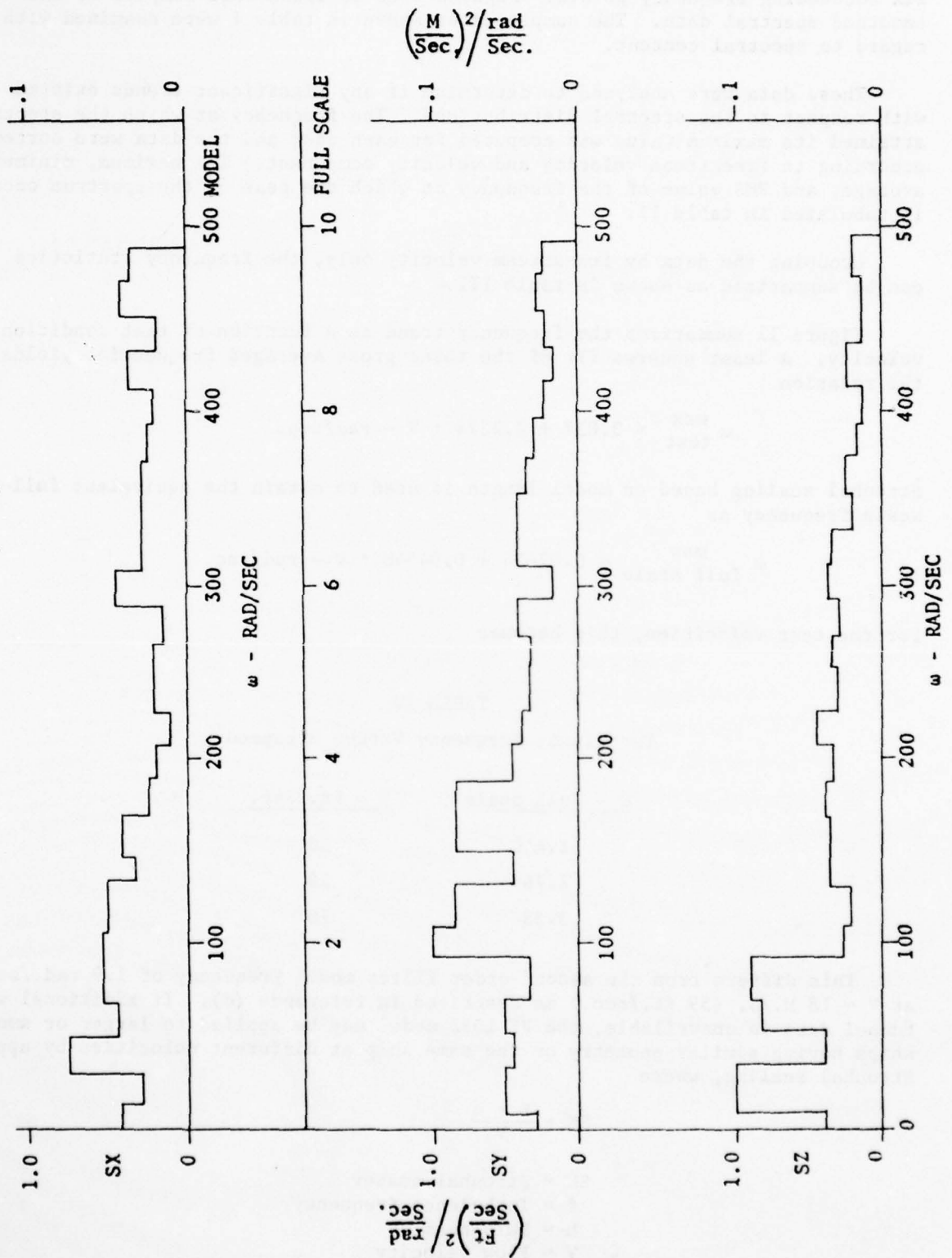
Figure 8 - Measured Gust Spectra, V = 9 M./Sec.,
X, Y, and Z Components
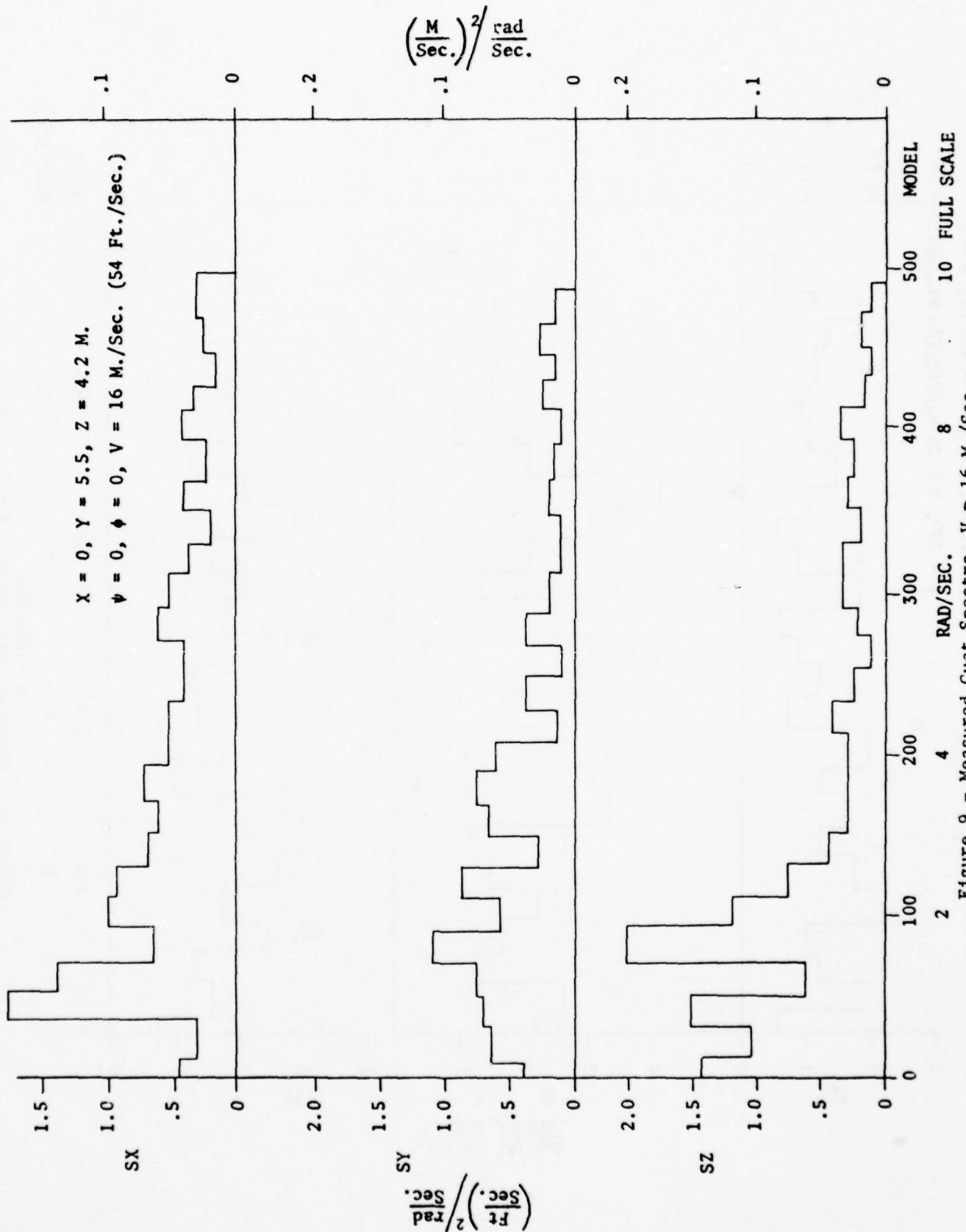
Figure 9 - Measured Gust Spectra, V = 16 M./Sec., X, Y, Z Components
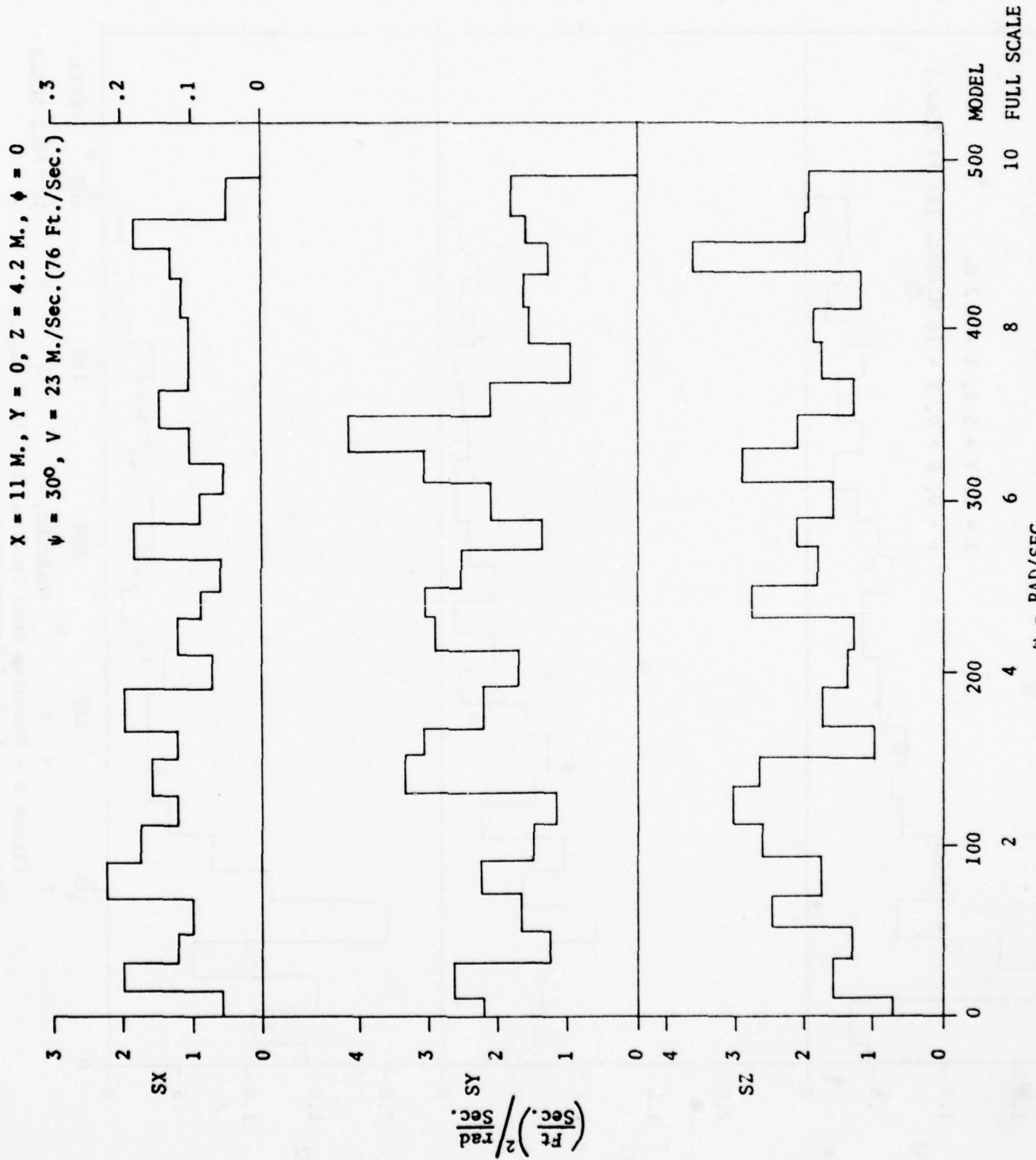
Figure 10 - Measured Gust Spectra, V = 23 M./Sec., X, Y, Z Components
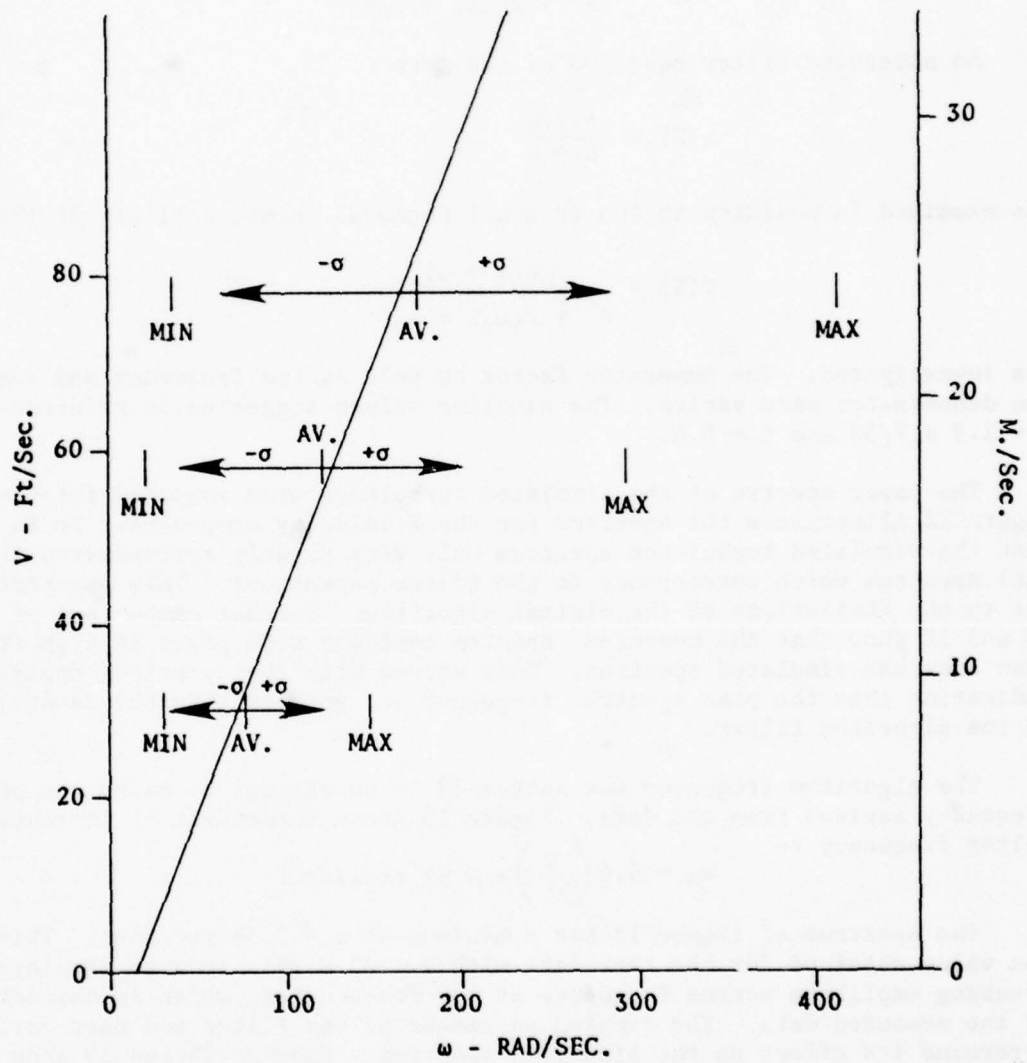
Figure 11 - Peak Spectral Frequency Versus Airspeed

The turbulence model was next examined to see how the properties of the simulated turbulence compared with the measured turbulence. The algorithm filter parameters were varied to determine if an improved match could be obtained between the simulated and test data turbulence. The basic filter equation proposed by reference (d) is

$$F(S) = \frac{\delta(x, y, z) \cdot \sqrt{4\zeta\omega_n^3}}{S^2 + 2\zeta\omega_n S + \omega_n^2}$$

An alternate filter equation of the form

$$F(S) = \frac{\delta \cdot / \sqrt{\omega}}{S + \omega}$$

was examined in addition to the original formula. Also, a filter of the form

$$F(S) = \frac{K(S + a)}{S^2 + 2\zeta\omega_n S + \omega_n^2}$$

was investigated. The numerator factor as well as the frequency and damping of the denominator were varied. The baseline values suggested in reference (d) were $\omega = 1.9 \times V/59$ and $\zeta = 0.4$.

The power spectra of the simulated turbulence were computed for $V = 23$ M./S. Figure 12 illustrates the spectrum for the X velocity component. It is apparent that the simulated turbulence spectrum only very roughly approximates the theoretical spectrum which corresponds to the filter parameters. This apparently occurs due to the limitations of the digital algorithm. Further comparison of figures 10 and 12 show that the measured spectra contains more power at high frequencies than does the simulated spectrum. This agreed with the previous analysis indicating that the peak spectral frequency was greater than the natural frequency of the algorithm filter.

The algorithm frequency was increased in an attempt to match the peak frequency derived from the data. Figure 13 shows the effect of increasing the filter frequency to

$$\omega_z = 4.6\left(\frac{V}{59}\right) = 5.93 \text{ rad./sec.}$$

The spectrum of figure 13 has a maximum at $\omega = 2.36$ rad./sec. This matches the value obtained for the test data with $V = 23$ M./S. It also displays an increasing amplitude versus frequency at low frequencies, which is characteristic of the measured data. The damping parameter of the filter was next varied to determine its effect on the simulated spectrum. Figures 14 and 15 show spectra with $\omega = 5.9$ and $\zeta = 0.1$ and 0.7.

Compared to the case with $\zeta = .4$, the configuration with $\zeta = 0.7$ had its peak amplitude at a lower frequency and lower amplitude at high frequencies. The $\zeta = 0.1$ case showed a large peak amplitude near the damped natural frequency and a rapid amplitude roll off at lower and higher frequencies. Thus, neither configuration appears to improve the correspondence with test data over that achieved with the original value of $\zeta = 0.4$.

$$\frac{(M./Sec.)^2}{rad/Sec.}$$

80 70 60 50 40 30 20 10 0 FULL SCALE

MODEL SCALE

28

$X = 0$, $Y = 0$, $Z = 4.2$ M.,

$\phi = 0$, $\psi = 50°$, $V = 23$ M/Sec.

$$F(S) = \frac{K}{S^2 + 2(.4)(2.45)S + (2.45)^2}$$

ω – RAD/SEC.

24   20   16   12   8   0
     1000 800 600 400 0

1200 1000 800 600 400 200 0

$$SX(\omega) \quad \frac{(Ft/Sec.)^2}{rad/Sec.}$$

TURBULENCE POWER DENSITY
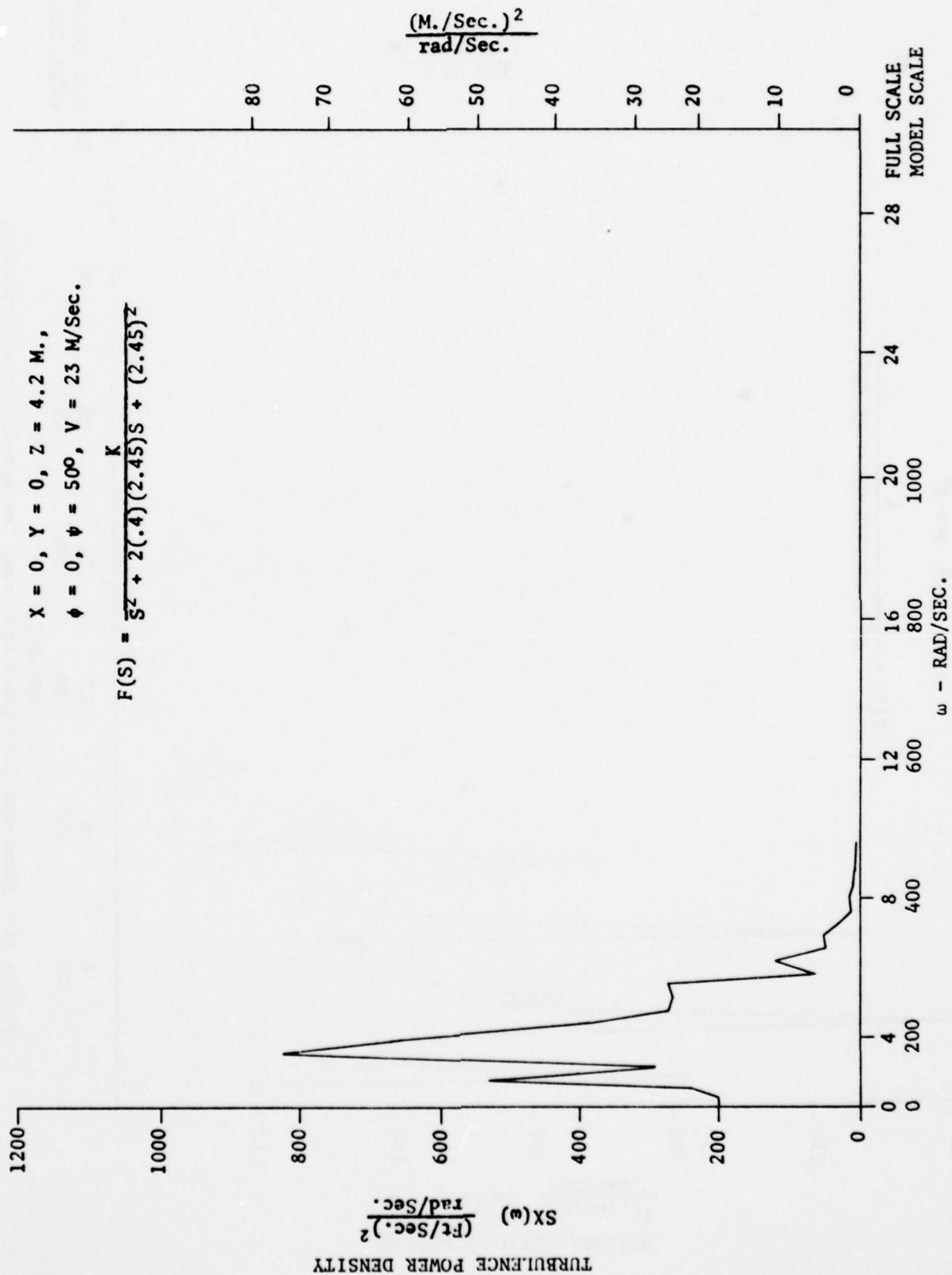
Figure 12 – Simulated Turbulence Spectrum, V = 23 M./Sec. (76 Ft/Sec.), X Velocity Component

- 29 -
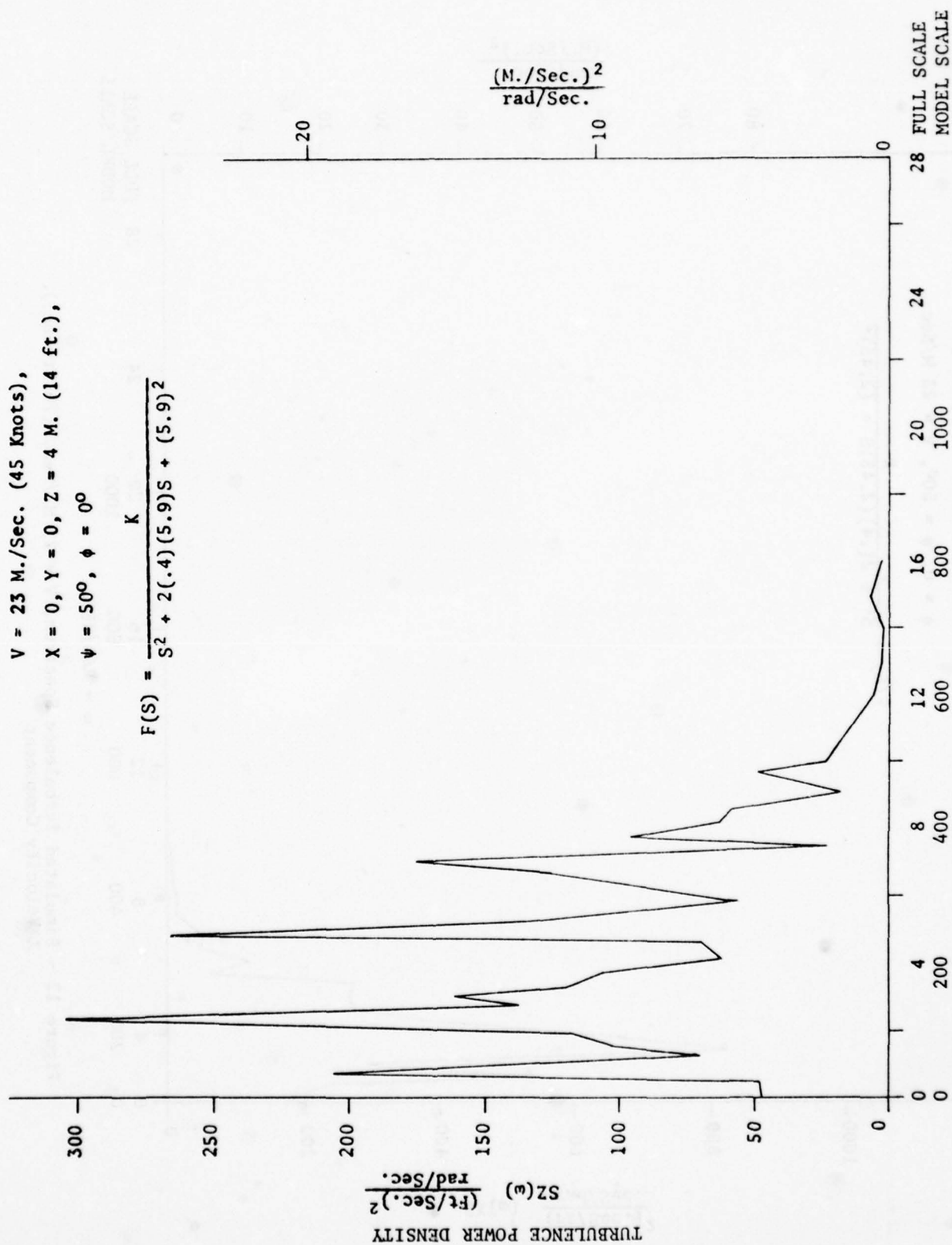
Figure 13 - Simulated Turbulence Spectrum, Increased Filter Frequency, Z Velocity Component

Figure 14 - Simulated Turbulence, 0.7 Damping,
Z Velocity Component

$V = 23$ M./Sec. (76 Ft/Sec.)

$\psi = 50^\circ$, $X = 0$, $Y = 0$, $Z = 4.2$ M.

$\phi = 0$

$$F(S) = \frac{K}{S^2 + 2(.1)(5.93)S + 5.93^2}$$
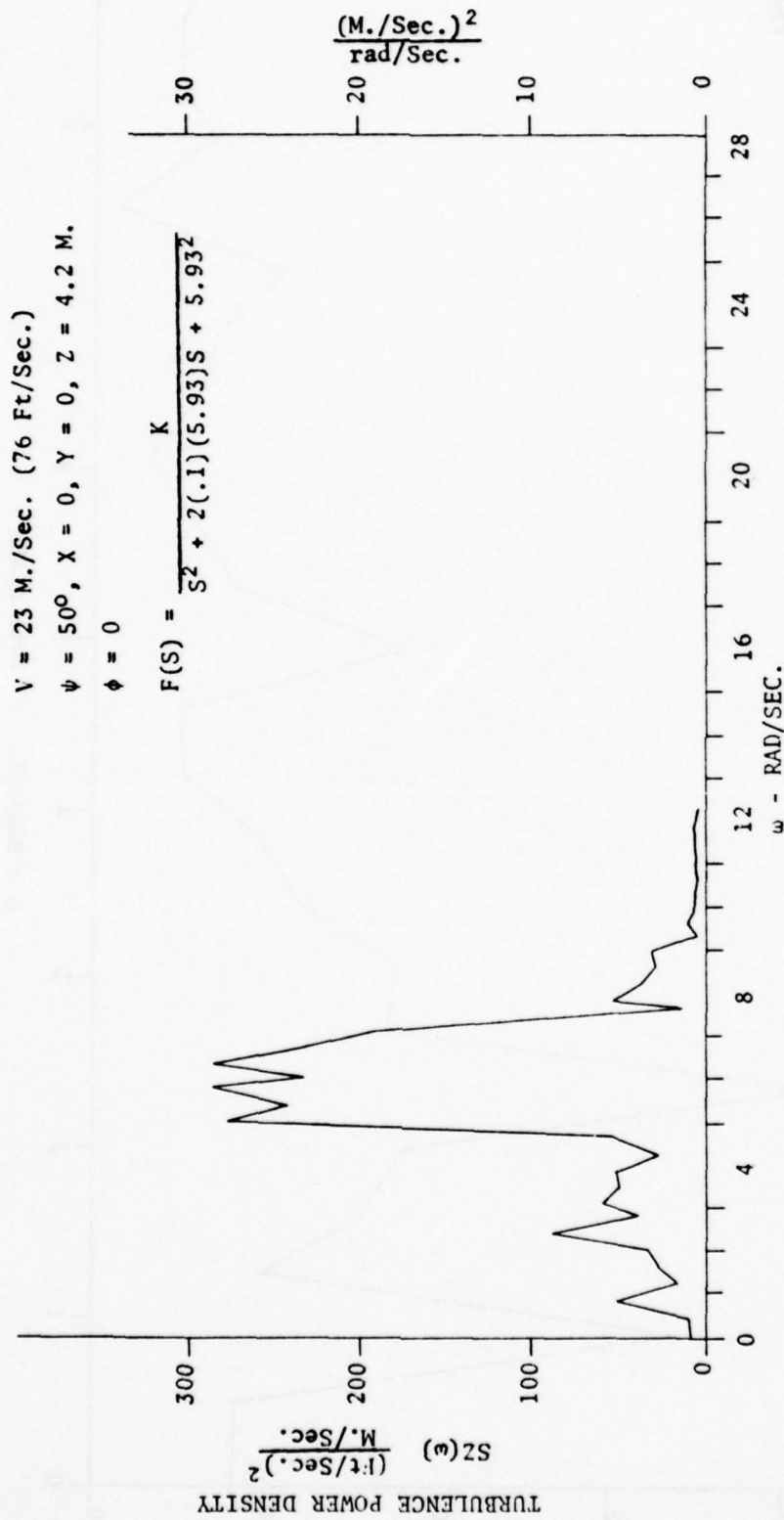
Figure 15 – Simulated Turbulence Spectrum, 0.1 Damping, Z Velocity Component

One additional filter configuration was examined in which a first-order numerator term was introduced with a break point at the denominator natural frequency. The resultant filter had the form

$$F(S) = \frac{K\ (S + \omega)}{S^2 + 2\ (0.4)\ \omega S + \omega^2}$$

A representative spectrum for this configuration is shown on figure 16. This configuration shows a more pronounced peak and a less rapid dropoff at high frequency than does figure 12. However, it does not appear to match the measured data as well as the configuration shown on figure 13.

Comparison of the various power spectra is found to be a less than conclusive method of establishing the proper form for a turbulence simulation. The measured data was limited to 256 point samples. Because of the extremely random nature of the turbulence, the short data sample appears inadequate to exactly define the power spectra. Even the artificially generated turbulence is found to have rather irregular spectra although the equations used in the algorithm should theoretically produce a smooth spectra. This may be caused by either the finite samples examined or by the approximations of the digital algorithm.

Because of difficulty in defining an exact mathematical relation for the spectra of either the measured turbulence or the simulated turbulence, the modeling effort was limited to matching the mean value, the variance, the frequency at which the power spectra attained its maximum value, and the overall slope of the spectrum above and below the peak frequency. Only the mean and variance can be matched in an exact manner by adjusting the mean functions and the random filter gains. The remaining characteristics must be established on a trial basis.

All of the second-order simulation models showed a more pronounced peak and a more rapid high frequency dropoff than did the test data. As a result, it was concluded that a first-order model might be more appropriate. The principal disadvantage of the first-order filter is that the output velocities tend to be more jerky and less smooth than those produced with a second-order filter. The problem was recognized as being caused by the way in which the random number sequences were generated. When a random number sequence is generated at each aircraft integration interval (typically 0.05 second), the bandwidth of the random noise sequence is high. The magnitude of a purely random sequence is essentially uncorrelated from one point to the next. In fact, turbulent velocity variations occur over finite times, and real measured data shows correlation over a very short time duration.

The apparent solution to this problem was to generate the random number sequence less frequently than the aircraft equations of motion were integrated. By interpolating linearly between succeeding random numbers, a smoothed input was generated which had limited bandwidth. By specifying the ratio of aircraft equation update interval to random number update interval, the power spectral content of the simulated turbulence could be more readily adjusted to match the test data.
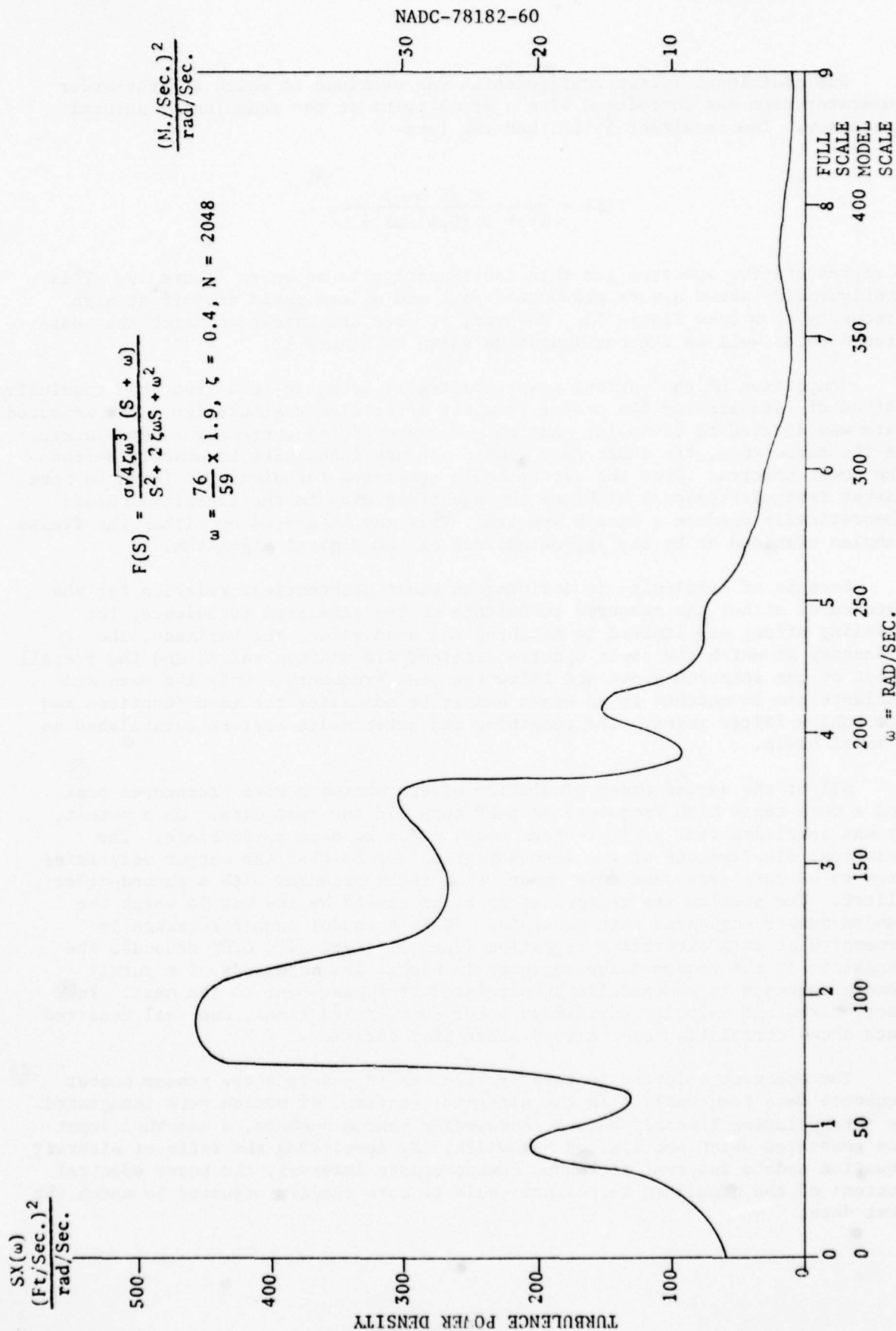
Figure 16 - Simulated Turbulence Spectrum, First Order Numerator

$$F(S) = \frac{\sigma\sqrt{4\zeta\omega^3}\,(S + \omega)}{S^2 + 2\zeta\omega S + \omega^2}$$

$$\omega = \frac{76}{59} \times 1.9, \quad \zeta = 0.4, \quad N = 2048$$

The smoothed random number sequence can be further processed to yield a reasonable simulation of the measured turbulence data by passing the number sequence through a properly designed first-order filter.

Because of the erratic nature of the measured data, it was decided to examine groups of points at various downstream ranges. Individual power spectra were normalized by dividing by their peak amplitudes. Then, these spectra were averaged on a component by component basis. The data selected included all cases for which $\phi = 0$, $\psi = 50$ deg, $V = 23$ M./Sec. The same process was performed for all data for which $\phi = 0$, $\psi = 50$ deg., and $V = 9$ M./Sec.

All points at a given downstream range were lumped together regardless of lateral position or height. Figures 17 to 20 show the effects of downstream station and freestream velocity on the character of the normalized spectra for the X, Y, and Z velocity components.

All four figures show a more pronounced dropoff of spectral amplitude with frequency for the X component than for the Y or Z components. Further, figures 17 and 18 show an overall lower frequency break point than do figures 19 and 20. This illustrates the fact that the turbulence frequency decreases as the distance downstream from the ship increases.

A least square straight line curve fit was first applied to the averaged test spectra. Then the break frequency of the first-order filter was assigned a value corresponding to the point at which the straight line reached a value of 0.5 times its value at zero frequency. This was chosen because the magnitude of

$$\left| \frac{1}{\frac{S}{\omega} + 1} \right|^2$$

reaches 0.5 at $S = \omega$. The curve fit analysis was applied to the cases for $V = 23$ M./Sec. (76 ft/Sec.).

Based on the assumption that Strouhal scaling could be applied, the filter frequency was made proportional to freestream velocity. The selected frequency was ratioed to the value obtained for the $V = 23$ M./S case by multiplying by $V/76$. The selected turbulence algorithm was then run repeatedly to obtain a good estimate of the spectral properties of the model. These spectra were averaged component by component and compared with the test spectra.

The filter break frequencies selected for $V = 23$ M./S., and $X = 0$ were as follows:

TABLE V

Filter Break Frequencies at X = 0

Component	Break Frequency (rad./sec.)
X	8.17
Y	10.41
Z	10.0
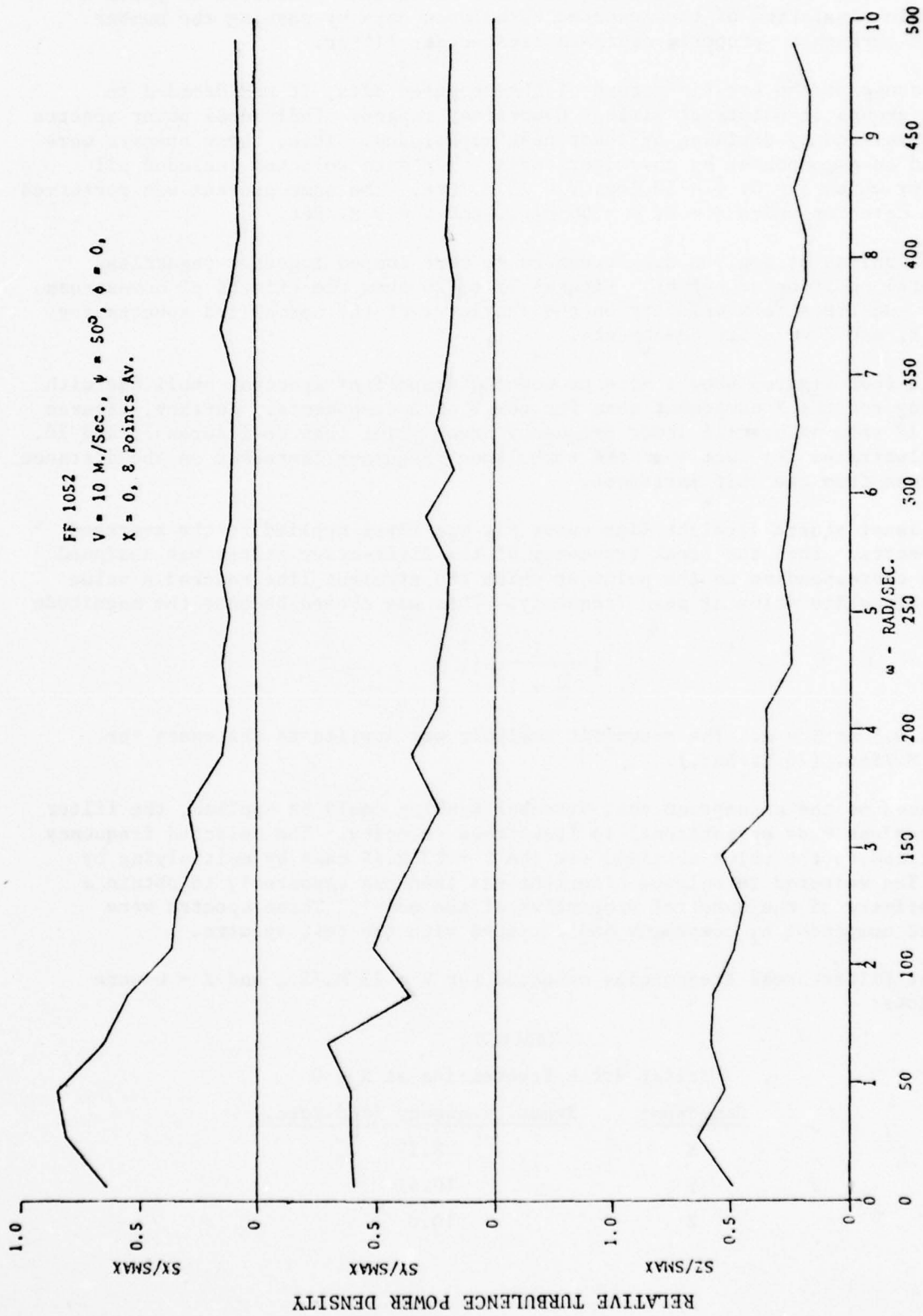
Figure 17 – Normalized Spectra for V = 10 M./Sec., X = 0 (Measured), X, Y, and Z Components
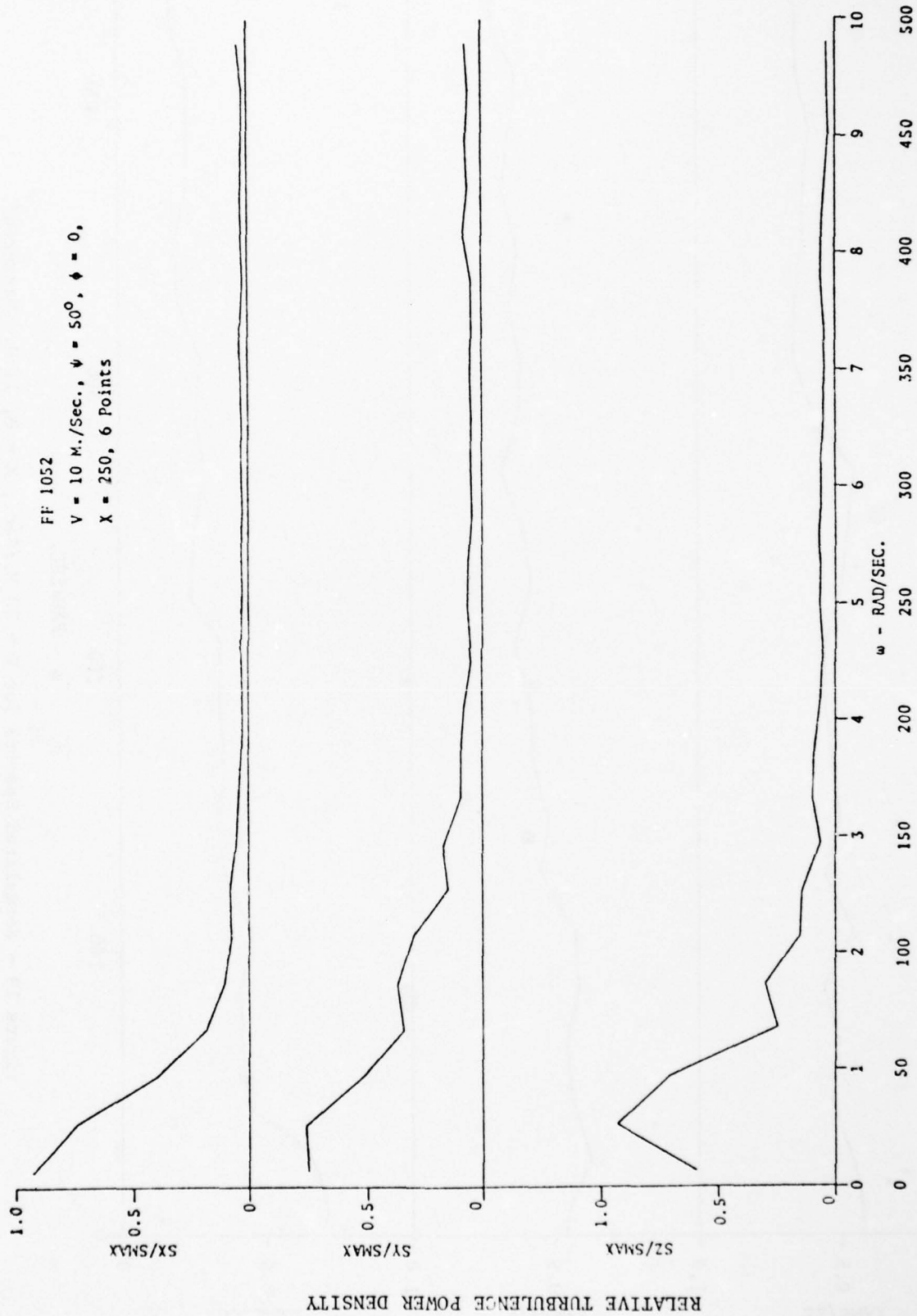
Figure 18 – Normalized Spectra for V = 10 M./Sec., X = 76 M. (Measured), X, Y, and Z Components
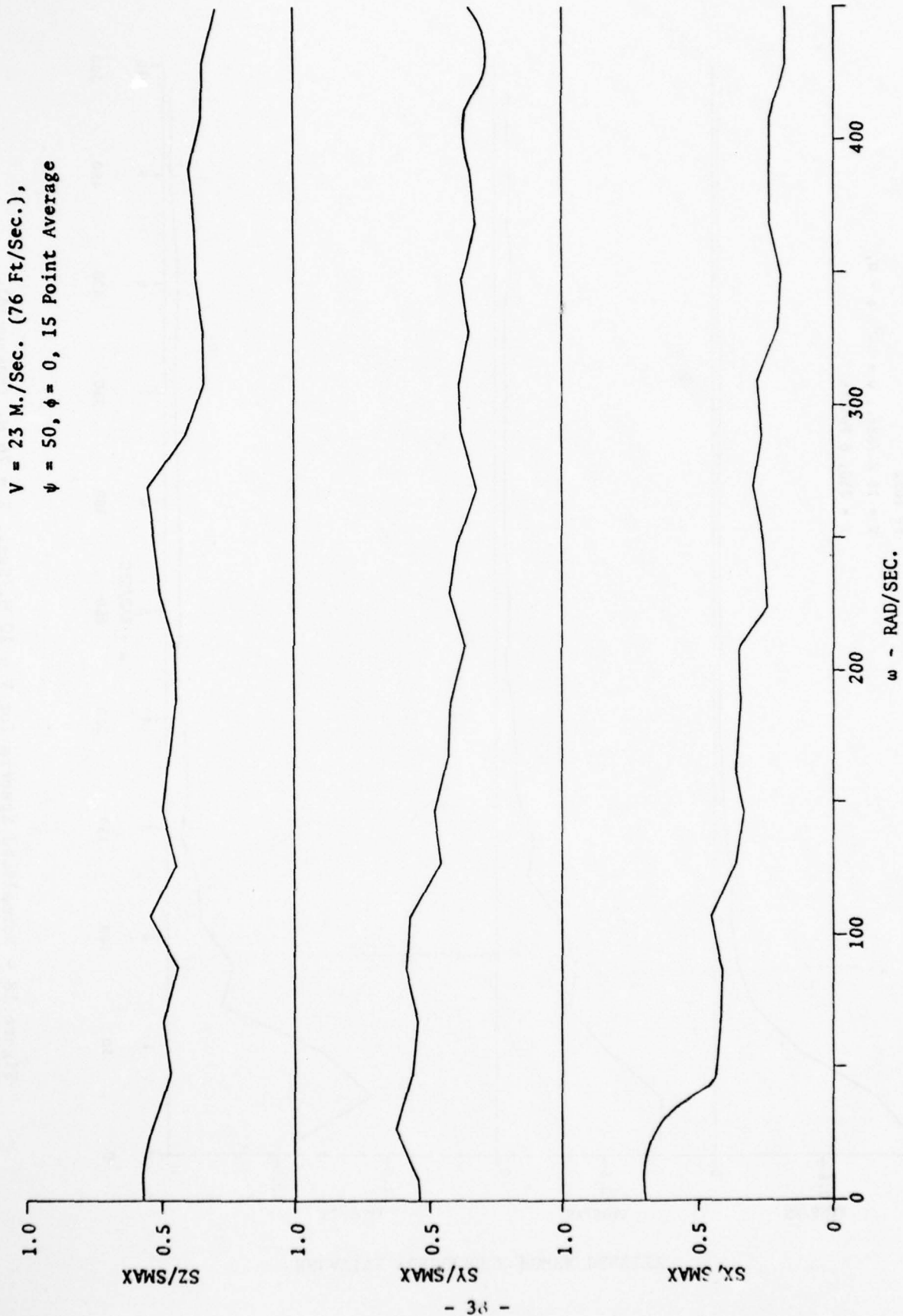
Figure 19 - Normalized Spectra for V = 23 M./Sec., X = 0, 11 M. (Measured), X, Y, and Z Components
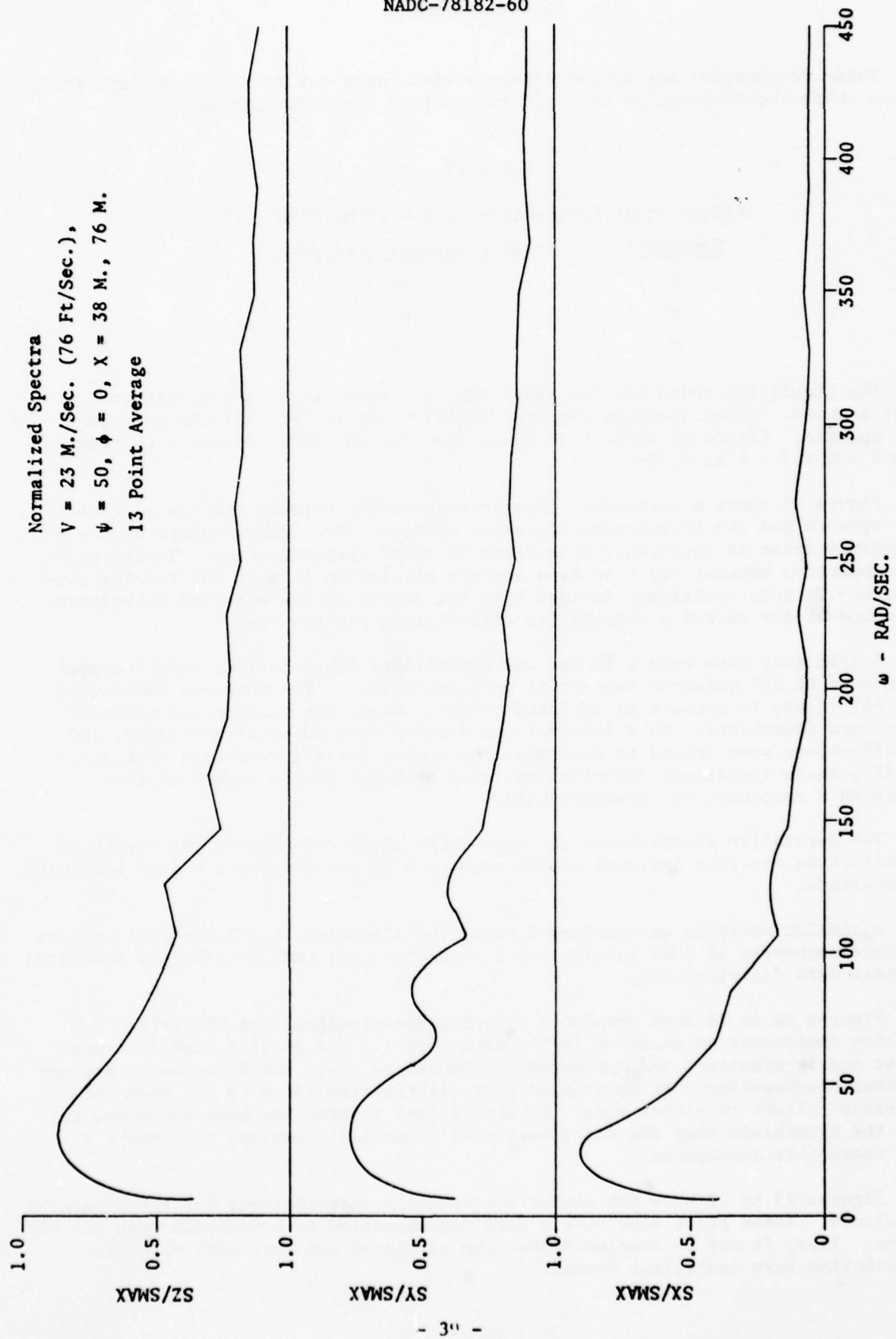
Figure 20 - Normalized Spectra for V = 23 M./Sec., X = 38 M., 76 M. (Measured),
X, Y, and Z Components

These frequencies are varied linearly with range out to X = 58 M. (190 ft.), beyond which the frequencies are held constant at the following values:

TABLE VI

Filter Break Frequencies at X = 58 M. (190 ft.)

Component	Break Frequency (rad./sec.)
X	1.58
Y	3.0
Z	2.88

The simulation model was run repeatedly to establish a representative power spectra. These averaged spectra were then plotted against the averaged test spectra. Figure 21 shows this comparison for the three velocity components with X = 0 and V = 23 M./Sec.

Figure 21 shows a reasonably good correspondence between the scaled test data spectra and the turbulence simulation spectra. The random nature of the turbulence makes it impossible to achieve an exact spectral match. Therefore, the comparison between the test data and the simulation data is not totally conclusive. To gain additional insight into the nature of the measured turbulence, the shape of the velocity probability distribution was examined.

Sample test data were selected and probability distributions were computed for groups of 256 measured sequential velocity values. The mean was subtracted from all values to produce an unbiased sample. Next, the maximum and minimum value were determined. This interval was divided into 20 equal divisions, and the 256 values were sorted to determine the number falling into each interval. Finally, these individual distributions were averaged over a number of test points on a component by component basis.

The derivative distribution was also computed by determining the change in velocity from one time interval to the next, and by sorting these values according to magnitude.

A similar analysis was performed using the simulated turbulence algorithm to generate sequences of 1024 points, and a comparison was made between the simulated and test data distributions.

Figures 22 to 24 show composite velocity distributions for the three velocity components as measured in the wind tunnel. The plotted distributions appear nearly symmetric and approximately Gaussian. Only the X component appears somewhat non-Gaussian. It shows a uniform distribution close to the mean with symmetric falloff to either side. No statistical testing has been performed to test the hypothesis that the distribution is Gaussian. However, it appears to be a reasonable assumption.

Figures 25 to 27 show the equivalent velocity distributions for the simulated turbulence. These plots also show a good approximation to a Gaussian type distribution. Thus, it may be concluded that the simulated and test data velocity distribution have equivalent forms.
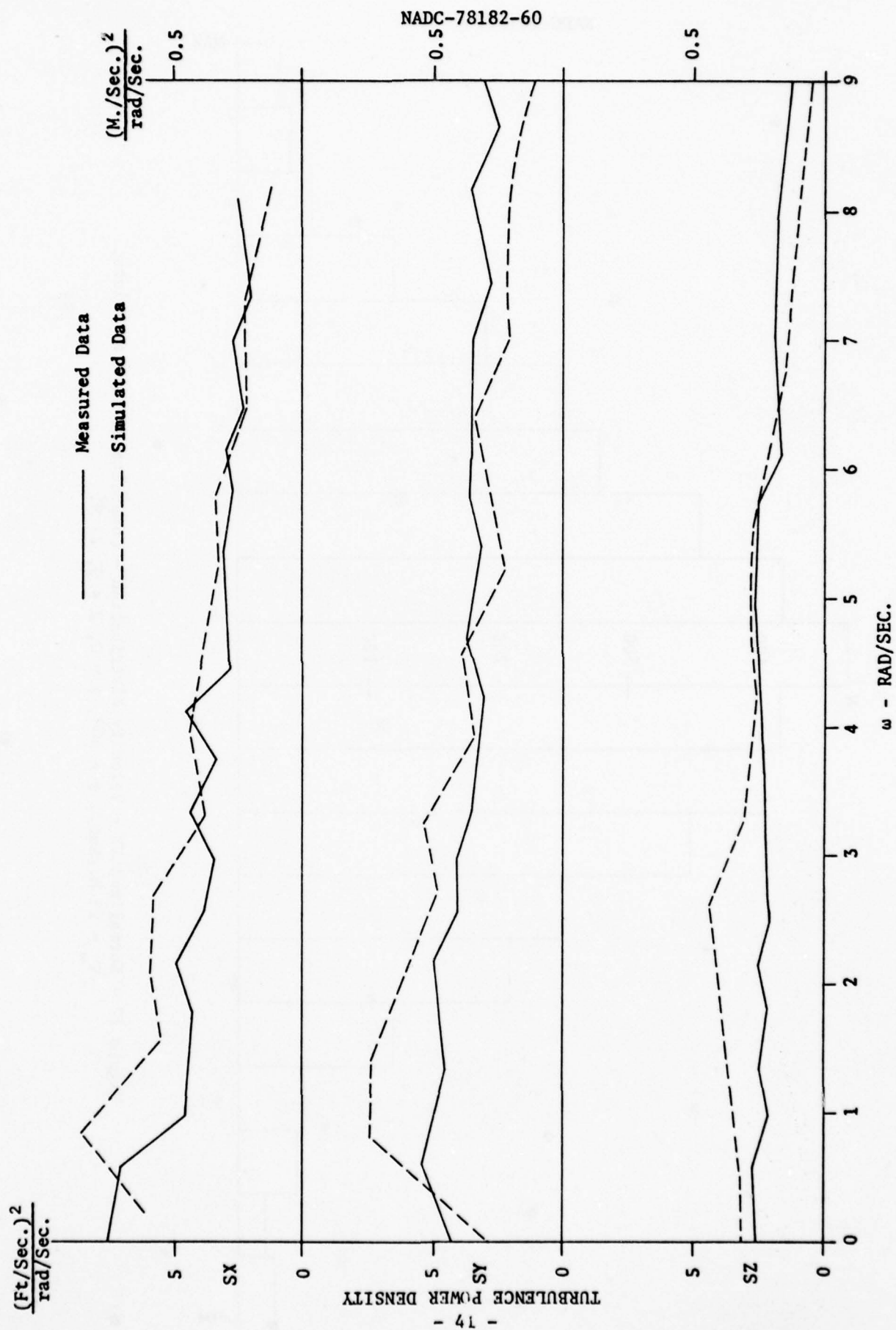
Figure 21 - Comparison of Test and Simulated Turbulence Spectra
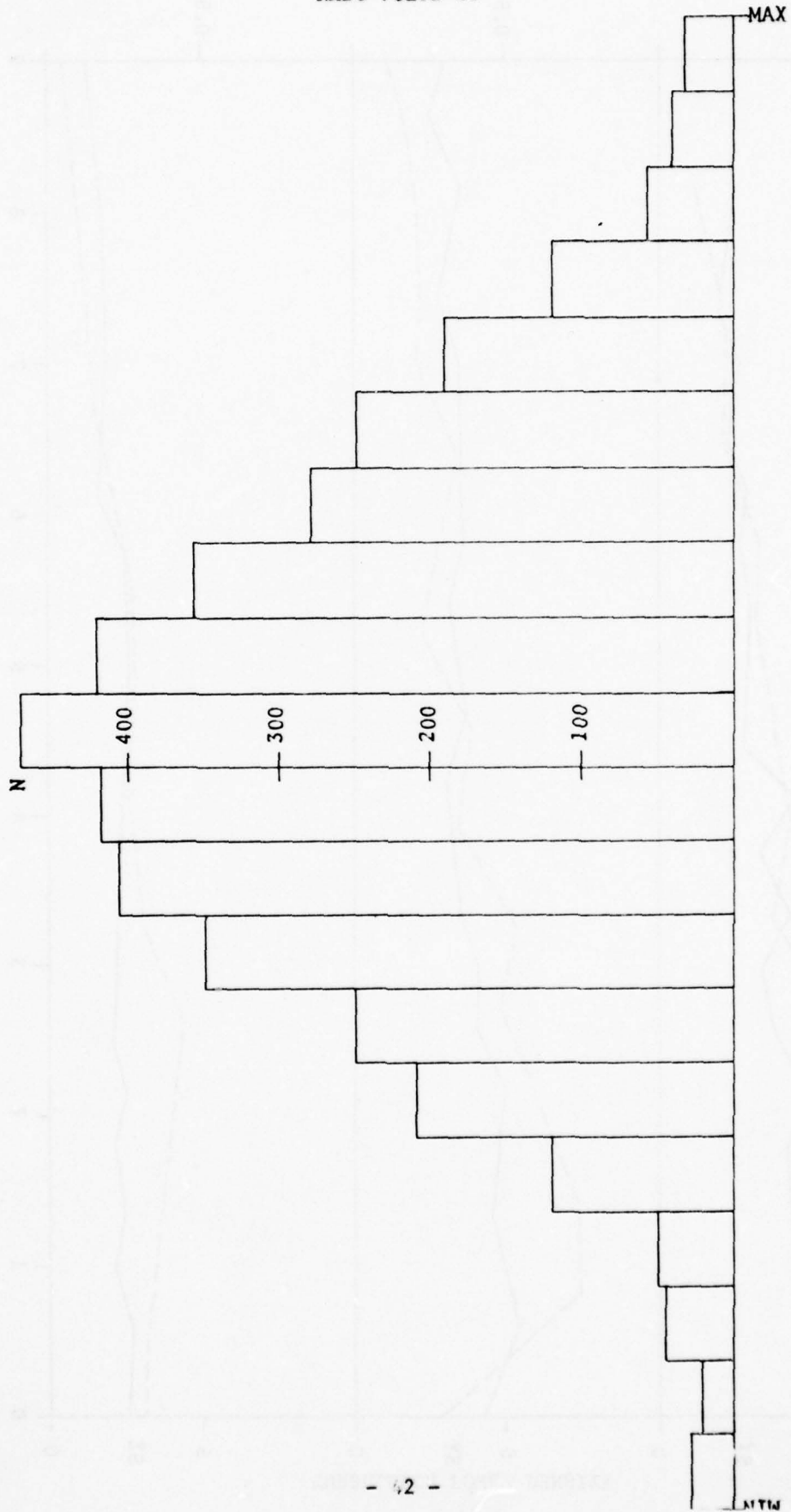
Figure 22 - Normalized VZ - Velocity Distribution - Composite of 16 Test Points, $V_\infty = 23$ M./Sec., $\psi = 50^\circ$, $\phi = 0$, $X = 0$, 27 M.

Figure 23 - Normalized VY - Velocity Distribution - Composite of 16 Test Points, $V_\infty = 23$ M./Sec., $\psi = 50°$, $\phi = 0$, $X = 0$, 27 M.
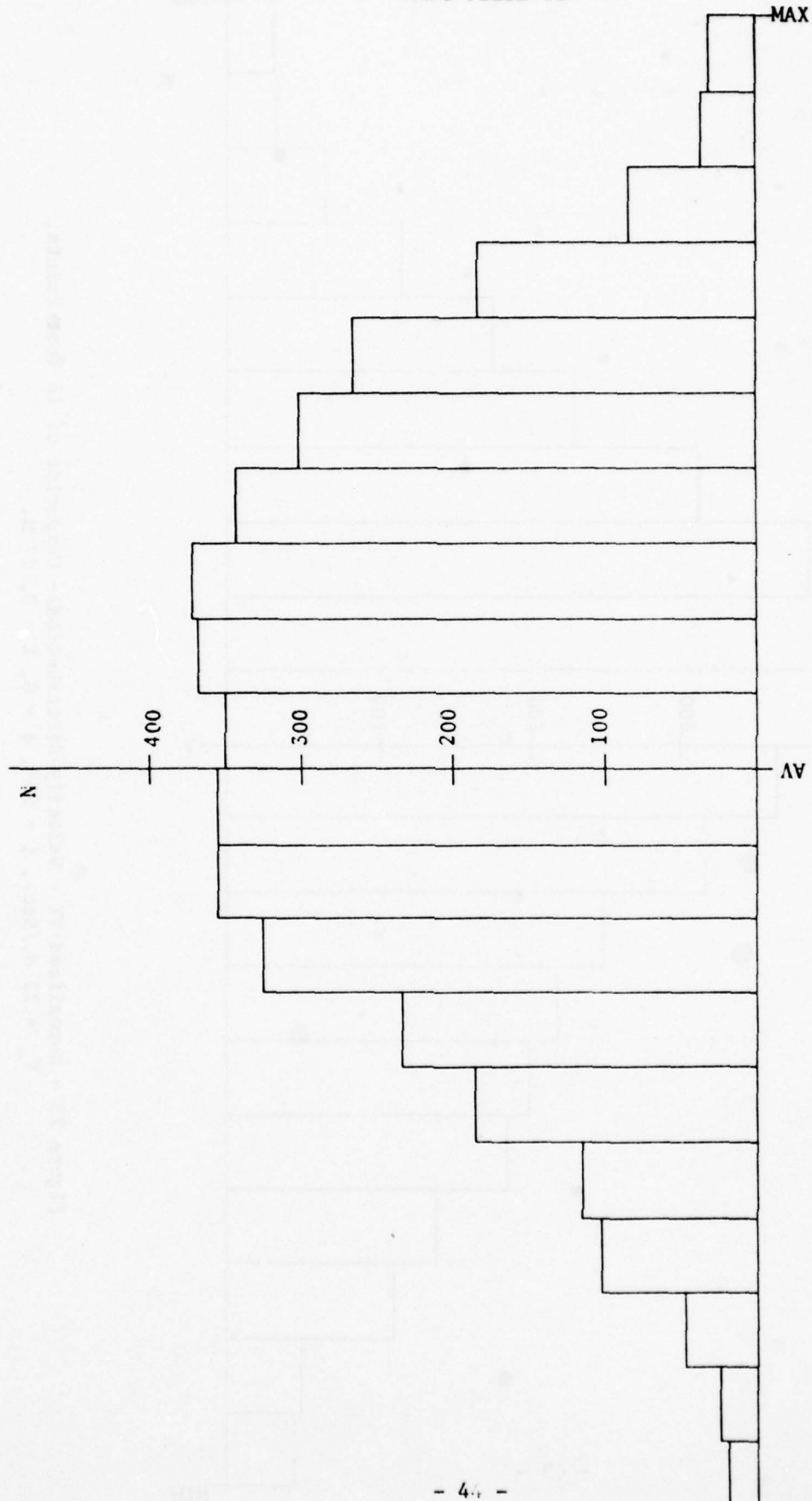
Figure 24 - Normalized VX - Velocity Distribution - Composite Average of 16 Test Points V_∞ = 23 M./Sec., ψ = 50°, ϕ = 0, X = 0, 27 M.
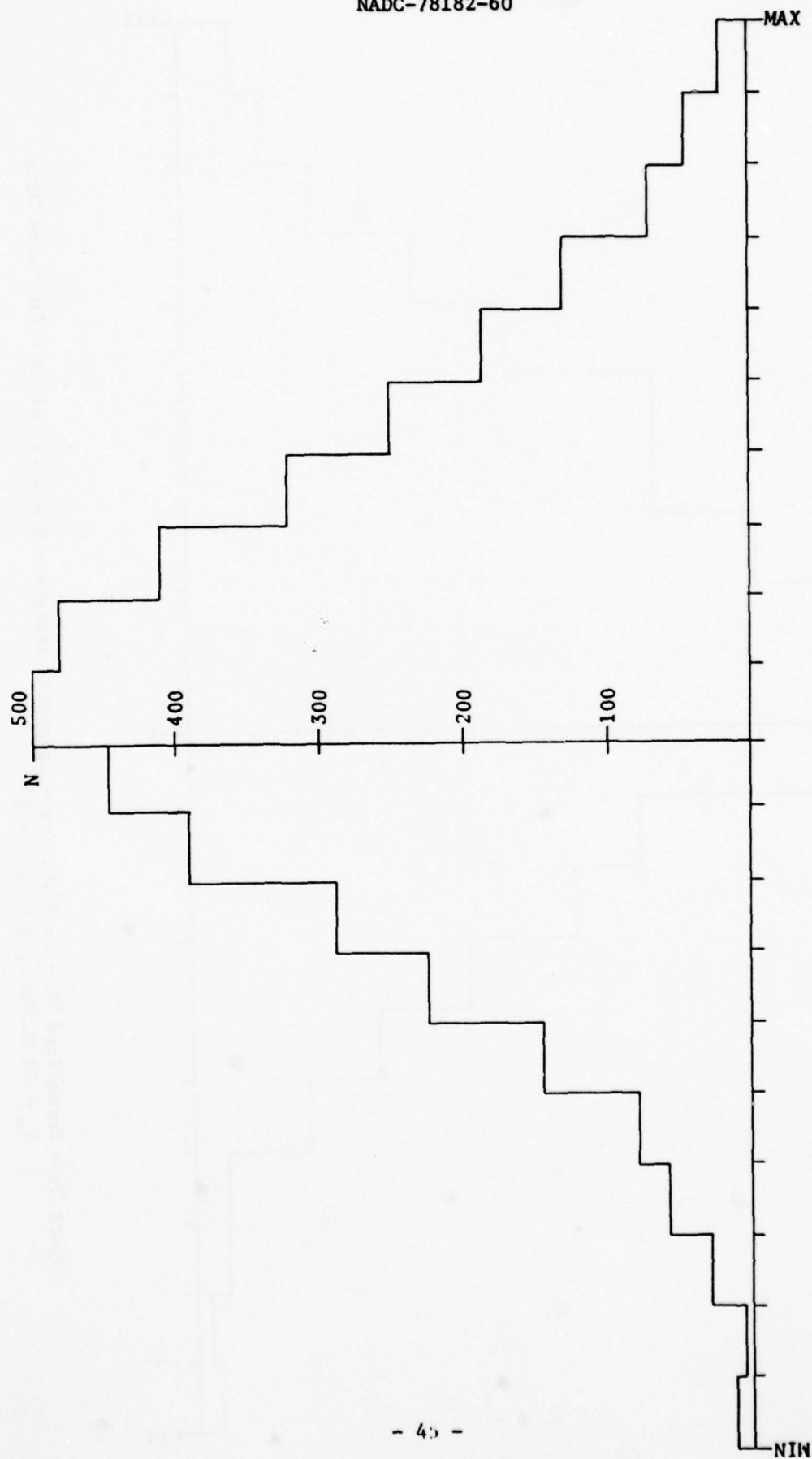
Figure 25 - Normalized VX - Distribution - Composite Average - 4 x 1024 Points - Simulated Data
V_∞ = 23 M./Sec., ϕ = 0, ψ = 50°
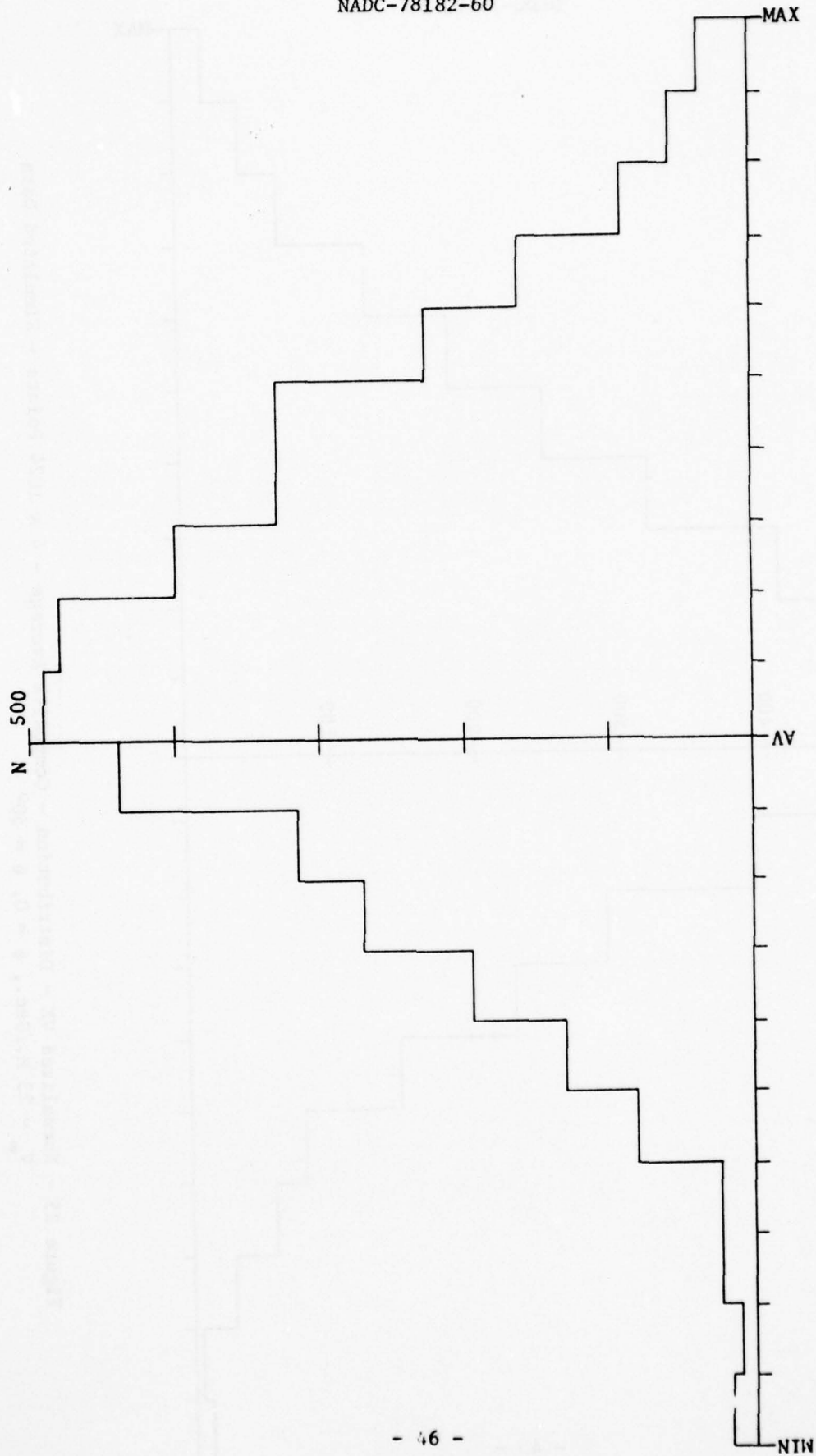
Figure 26 - Normalized VY - Distribution - Composite Average - 4 x 1024 Points - Simulated Data V_∞ = 23 M./Sec., ϕ = 0, ψ = 50°
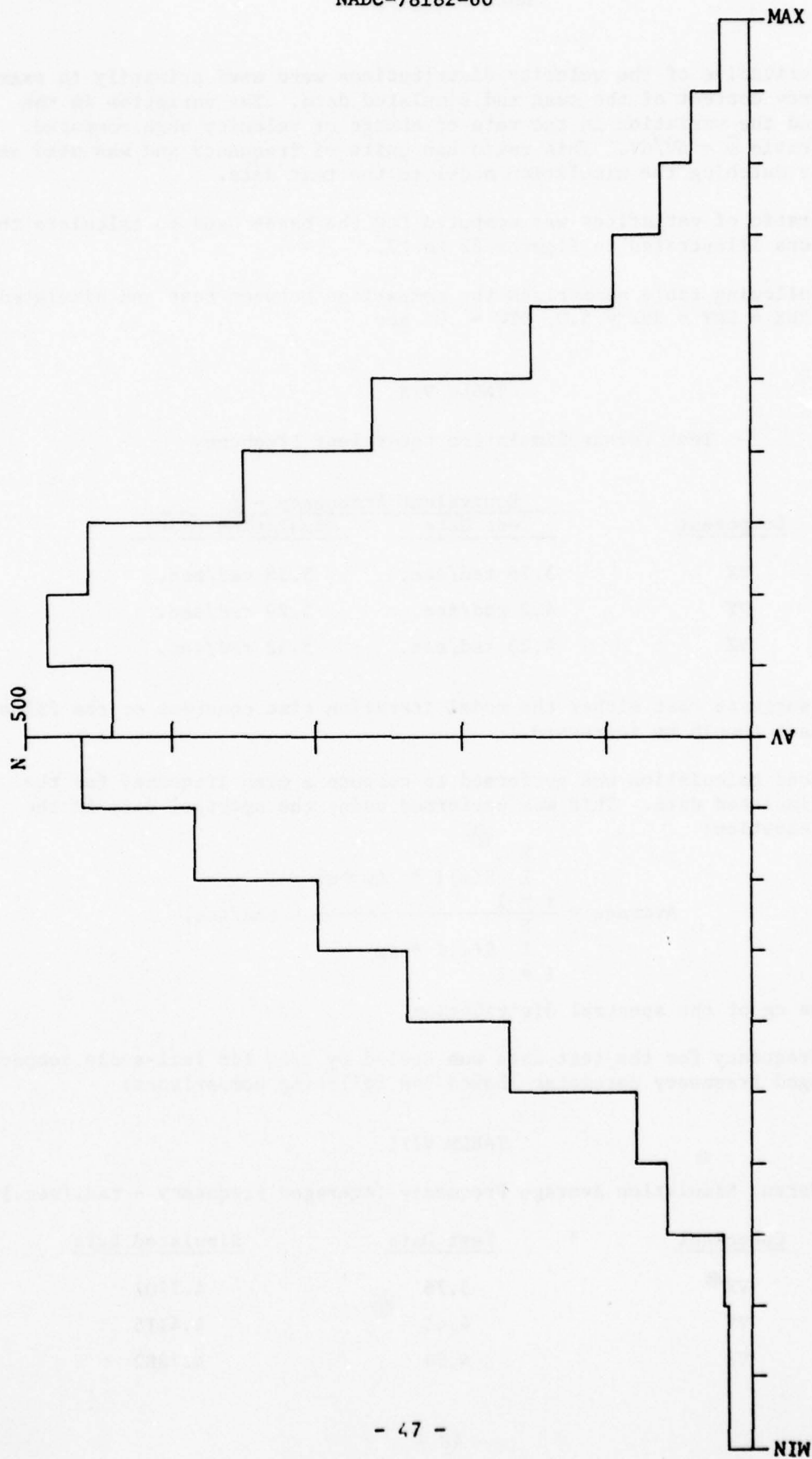
Figure 27 - Normalized VZ - Distribution - Composite Average - 4 x 1024 Points - Simulated Data
$V_\infty = 23$ M./Sec., $\phi = 0$, $\psi = 50°$

The derivative of the velocity distributions were used primarily to examine the frequency content of the test and simulated data. The variation in the velocity and the variation in the rate of change of velocity were computed. Then, the ratio $\bar{\omega} = \delta\dot{V}/\delta V$. This ratio has units of frequency and was used as a basis for matching the simulation model to the test data.

This ratio of variations was computed for the cases used to calculate the distributions illustrated in figures 22 to 27.

The following table summarizes the comparison between test and simulated data with RNX = RNY = RNZ = 5.0, DTW = .05 sec.

TABLE VII

Test Versus Simulation Equivalent Frequency

| | Equivalent Frequency $\bar{\omega}$ | |
Component	Test Data	Simulation Model
VX	3.78 rad/sec.	5.38 rad/sec.
VY	4.2 rad/sec.	5.29 rad/sec.
VZ	4.23 rad/sec.	5.52 rad/sec.

This suggests that either the model iteration time constant or the filter time constant should be increased.

A second calculation was performed to compute a mean frequency for the test and simulated data. This was performed using the spectral data in the following equation:

$$\text{Average} = \frac{\displaystyle\sum_{i=1}^{N} S(\omega)i * \Delta\omega * \omega i}{\displaystyle\sum_{i=1}^{N} S(\omega)i * \Delta\omega} - \text{rad/sec.}$$

This is the cg of the spectral distribution.

The frequency for the test data was scaled by 1/50 for full-scale comparison. This averaged frequency parameter showed the following comparisons:

TABLE VIII

Test Versus Simulation Average Frequency (Averaged Frequency – rad./sec.)

Component	Test Data	Simulated Data
VX	3.76	4.7707
VY	4.44	4.4115
VZ	4.54	4.7282

The fact that the equivalent frequency of all three components of the simulated turbulence is nearly identical in spite of differences in the filter constants suggests that the random number calling interval dominates the spectral distribution of the simulated turbulence. Therefore, the program scale factors RNX, RNY, and RNZ were adjusted from initial values of 5.0 to RNX = 7.12, RNY = 6.3, and RNZ = 6.52 based on the ratios of the equivalent frequency parameter. For these parameters, the equivalent and average frequencies compare as follows:

TABLE IX

Test Versus Adjusted Simulation Frequency

Component	Test		Simulation	
	ω	ωAv	ω	ωAv
VX	3.78	3.76	4.51	3.64
VY	4.2	4.44	4.63	3.68
VZ	4.23	4.54	4.65	3.79

Given the accuracy of the analysis and the limited sample size examined, this appears to represent a near optimum match. Figure 28 illustrates the resulting spectra for a single simulation run.

CORRELATION ANALYSIS

Certain test data points were selected for correlation analysis. The auto-correlation and cross-correlation functions were computed to determine if the gusts were purely random or if any time or space correlation existed. The equation used was

$$R_{XY}(N) = \frac{\sum\limits_{i=N}^{M} \dfrac{(VX_i - \bar{VX}) \cdot (VY_{i-N} - \bar{VY})}{(M - N)}}{\sqrt{\left(\sum\limits_{i=N}^{M} \dfrac{(VX - \bar{VX})(VX - \bar{VX})}{M}\right) \cdot \left(\sum\limits_{i=1}^{M} \dfrac{(VY - \bar{VY})(VY - \bar{VY})}{M}\right)}}$$

As expected, the autocorrelation functions were found to have unit values for zero time shift, but were close to zero for all non-zero time shift values. This means that no significant periodicity exists in the measured data. Most of the crosscorrelation functions were found to be essentially zero for all time shift values. The condition examined was $X = 0$, $Y = 0$, $\psi = 50^{\circ}$, $\phi = 0^{\circ}$, $H = 4.2$, 7.6 M. There was no space correlation between velocities at $H = 4.2$ M. and $H = 7.6$ M. above deck.

The only significant crosscorrelation uncovered was between the X and Y components at $H = 4.2$ M. (14 ft.) This can be interpreted as a vorticity in the wind velocity about the Z axis at this point. This corresponds to an aircraft
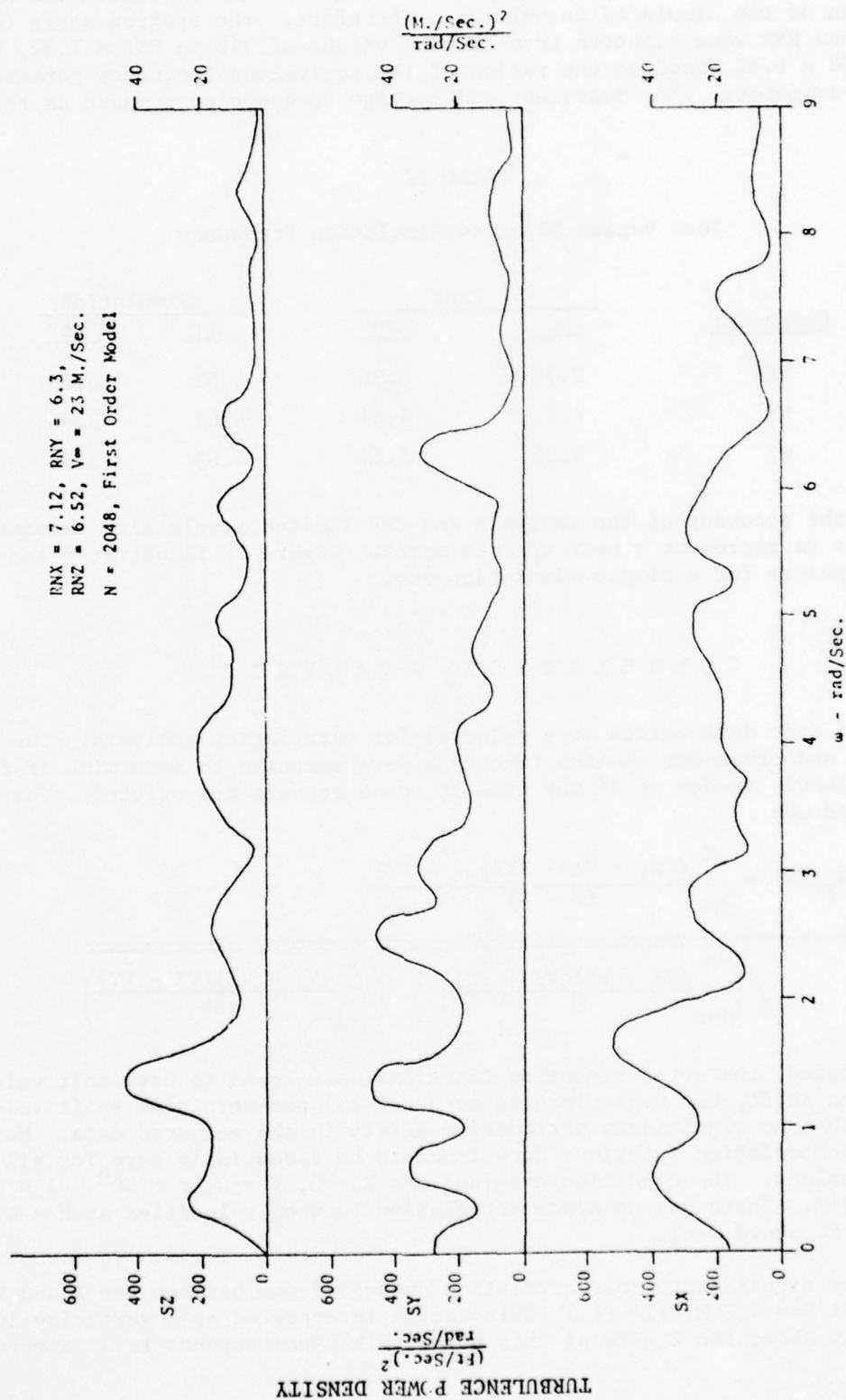
Figure 28 - Simulated Spectra With Adjusted Time Constants,
X, Y, Z Components

TABLE X

Correlation Summary of Test Data $V_\infty = 23$ M./S., $\psi = 50^o$, $\phi = 0$

Point 1: $X = 0$, $Y = 0$, $Z = 4.2$ M.

Point 2: $X = 0$, $Y = 0$, $Z = 7.6$ M.

$\Delta T = 0.0061$ second model scale

$= 0.31$ second full scale

Components		ΔT-Shift 0	1	2
X_1	X_1	1.0	0.288	−0.057
Y_1	Y_1	1.0	−0.08	−0.1
Z_1	Z_1	1.0	0.064	−0.014
X_1	Y_1	−0.544	−0.154	0.094
Y_1	Z_1	−0.05	−0.05	0.08
X_1	Z_1	−0.1	0.04	0.018
X_2	X_2	1.0	0.24	−0.01
Y_2	Y_2	1.0	−0.08	−0.002
Z_2	Z_2	0.998	−0.058	−0.206
X_2	Y_2	−0.303	−0.129	0.0409
Y_2	Z_2	0.0974	−0.081	−0.095
X_1	Z_2	−0.1	−0.001	0.08
X_1	X_2	0.237	0.16	−0.074
Y_1	Y_2	0.284	0.0107	−0.074
Z_1	Z_2	0.143	0.0446	0.0455
X_1	Y_2	−0.15	−0.076	−0.076
Y_1	Z_2	0.075	−0.174	−0.0216
X_1	Z_2	−0.096	0.121	0.171

yaw rate. It is not clear whether this has a significant effect on aircraft motion so that provision for including this effect should be added to the model. The effect does not appear strong enough to justify additional complexity in the model.

SENSITIVITY ANALYSIS OF THE EFFECTS
OF THE ASSUMED FORM OF THE
TURBULENCE SPECTRUM

Evaluation of the test data and the various model algorithms do not lead to an exact and definite conclusion regarding the values of the model parameters.

A question arises as to whether the exact turbulence spectrum must be duplicated by the model in order to yield a useful analytical tool. In an attempt to answer this question, the closed-loop pitch response to horizontal gusts was computed using the original second-order model format. RMS pitch response was computed for a range of spectral gust frequency model parameters. A closed-loop pitch transfer function was calculated for a representative VSTOL (AV8A) at a 62 M./S. (120 knot) transition condition. The pitch loop was closed with a simple gain pitch SAS and pilot model incorporating pitch attitude and pitch rate feedback through a delay.

The closed-loop pitch to horizontal gust transfer function was calculated and the RMS gust response was then determined using the equation:

$$\delta\theta^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left| \frac{N \, \overset{\theta}{ug}}{D} \right|^2 \phi_{ugust}(jw) \cdot dw$$

where $\dfrac{N \, ug}{D}$ is the closed-loop transfer function

and ϕ_{ugust} is the gust power spectrum.

The gust power spectrum is developed by squaring the magnitude of the gust transfer function as follows

$$\frac{\text{Gust Velocity}}{\text{Random Input}}(S) = \frac{\delta \cdot 2 \cdot \sqrt{\zeta\omega^3}}{S^2 + 2\zeta\omega + \omega^2}$$

$$\phi_{gust}(S) = \frac{\delta^2 \, 4 \, \zeta\omega^3}{(S^2 + 2\zeta\omega S + \omega^2)(S^2 - 2\zeta\omega S + \omega^2)}$$

The system block diagram is illustrated by figure 29.

The closed-loop gust transfer function then becomes

$$\frac{\theta}{ug}(S) = \frac{(3.28)(S + 8)(-0.002832S^2 + 0.0005604S + 0.0003527)}{(S^5 + 7.046S^4 + 17.9199S^3 + 27.827S^2 + 16.692S + 2.8202)}$$
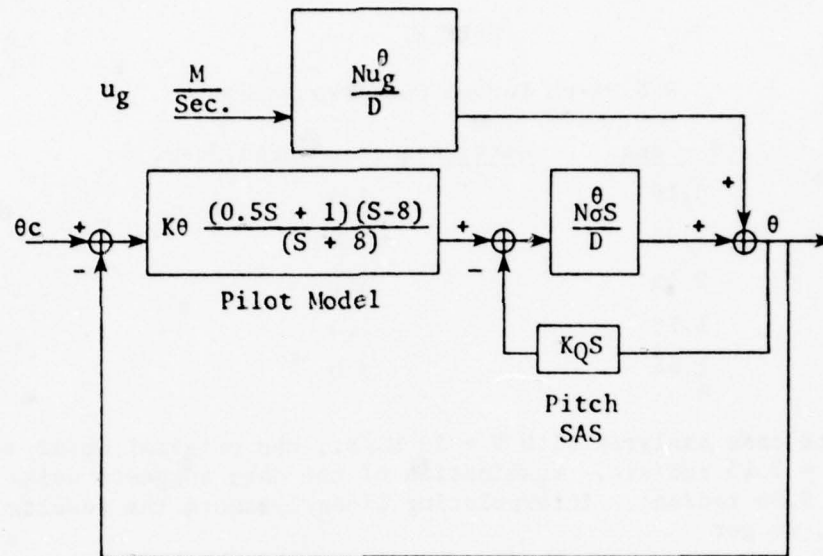
$$N\overset{\theta}{\sigma}S = -8.057 \ S^2 - 5.218 \ S - .823 \ \text{Rad./rad.}$$

$$D = S^4 + 0.7382 \ S^3 - 0.9896 \ S^2 - 0.2859 \ S + 0.006864$$

$$N u\overset{\theta}{g} = 3.28 \ X \left(-0.002832 \ S^2 + 0.0005604 \ S + 0.0003527\right) \frac{\text{Rad}}{\text{M./Sec.}}$$

$$K\theta = 0.42 \ \text{rad/rad.}$$

$$K_Q = -0.49 \ \text{rad/rad/sec.}$$

Figure 29 - Closed-Loop Gust Response Transfer Function

RMS gust responses were calculated for the following parameters

σ_{ug} = 7.1 M./S. (23.3 ft/sec.), ζ = 0.4, ω = 1.4, 2, 3, 5, and 7 rad/sec.

The results follow:

TABLE XI

RMS Pitch Versus Gust Frequency

$\sigma\theta$ - deg.	Gust Frequency - rad./sec.
3.16	1.4
2.95	2.0
2.43	3.0
1.76	5.0
1.44	7.0

For the data case analyzed with V = 23 M./S., the original model uses ω_x = 1.9 x V/59 = 2.45 rad/sec. Examination of the data suggests using ω_x = 3 x V/18 = 3.86 rad/sec. Interpolating linearly among the results from the sample case, we get

$\sigma\theta$ - deg.	ω - rad./sec.
2.72	2.45
2.14	3.86

This corresponds to a 21-percent difference in sigma values for a 64-percent variation in frequency.

Thus, the frequency of the gust model does significantly affect the aircraft response for constant RMS gusts. However, a gust model which predicts gust response to within 10 percent would probably be a satisfactory tool. Thus, the assumed filter algorithm is not extremely critical. The sensitivity shown by the sample indicate that it would be sufficient to define the frequency parameter to within 25 percent of its true value. In contrast, the aircraft response varies directly with RMS gust amplitude. Thus, it is most important to accurately match the gust RMS amplitude.

TIME HISTORY COMPARISON

One final comparison of the simulated and measured turbulence was made by plotting the velocity time histories of the three velocity components. The case selected was

$$X = 0 \qquad V_\infty = 23 \text{ M./S.}$$
$$Y = 0 \qquad \psi = 50^\circ$$
$$Z = 4.2 \text{ M.} \qquad \phi = 0$$

The experimental data was recorded at a time interval of 0.0061 second. This value was scaled up by a factor of 50 to yield a plot scale interval of 0.31 second. Simulated data points were calculated at a 0.05-second time interval. Because of the measurement interval, the bandwidth of the experimental data was limited to 10.13 rad./sec. Thus, higher frequency oscillations might have been present, but they could not be detected.

The simulated and test velocity sequences were compared on the basis of maximum, minimum, mean, and variance values as well as a qualitative comparison of the shapes of the plotted sequences. Figures 30 to 32 illustrate the relationships for the three velocity components. The mean and variance values compare well for all three components. The maximum and minimum values seem consistent in all cases with the magnitudes of the mean and variances.

A qualitative comparison of the number of local maxima and minima in a 10-second period show that the frequency content of the simulated and measured velocities compare satisfactorily.

RESULTS AND CONCLUSIONS

The CVA turbulence model contained herein remains basically unchanged from the version described in reference (c) as a result of analysis performed for this study. It is suitable for simulation of aft approaches and forward takeoffs of conventional and VSTOL aircraft.

The FF 1052 turbulence model is designed to permit VSTOL takeoff and landings from any angle. Wind conditions are currently limited to relative wind angles of 0, 30, and 50 degrees at total velocities of 10, 18, and 23 M./S. (20, 35, and 45 knots).

After considerable iteration, the FF1052 turbulence model structure was fixed with these features:

1. Exponential and linear extrapolation of tabulated mean and variance velocity values beyond the region of measured data.

2. First-order exponential filtering of random number inputs using inverse time constants that decrease linearly with range downstream.

3. The random number subroutine used to generate the three gust velocities are called less frequently than the basic simulation loop time, and the resultant random number sequences are linearly interpolated.

4. The random number update interval is selected to match test data spectral distributions.

5. The filter time constants vary inversely with freestream steady velocity.

6. The frequency content of the three velocity components display different characteristics with the horizontal component having a lower frequency spectrum than the Y and Z components.

M./Sec.

Simulation Test Sample		
V̄	40.7	39.3 Ft/Sec.
σ	24.3	23.3 Ft/Sec.
VMAX	92.6	93.9 Ft/Sec.
VMIN	-30.4	-22.4 Ft/Sec.

TIME - SEC.

Simulate

Test

VX - Ft/Sec.
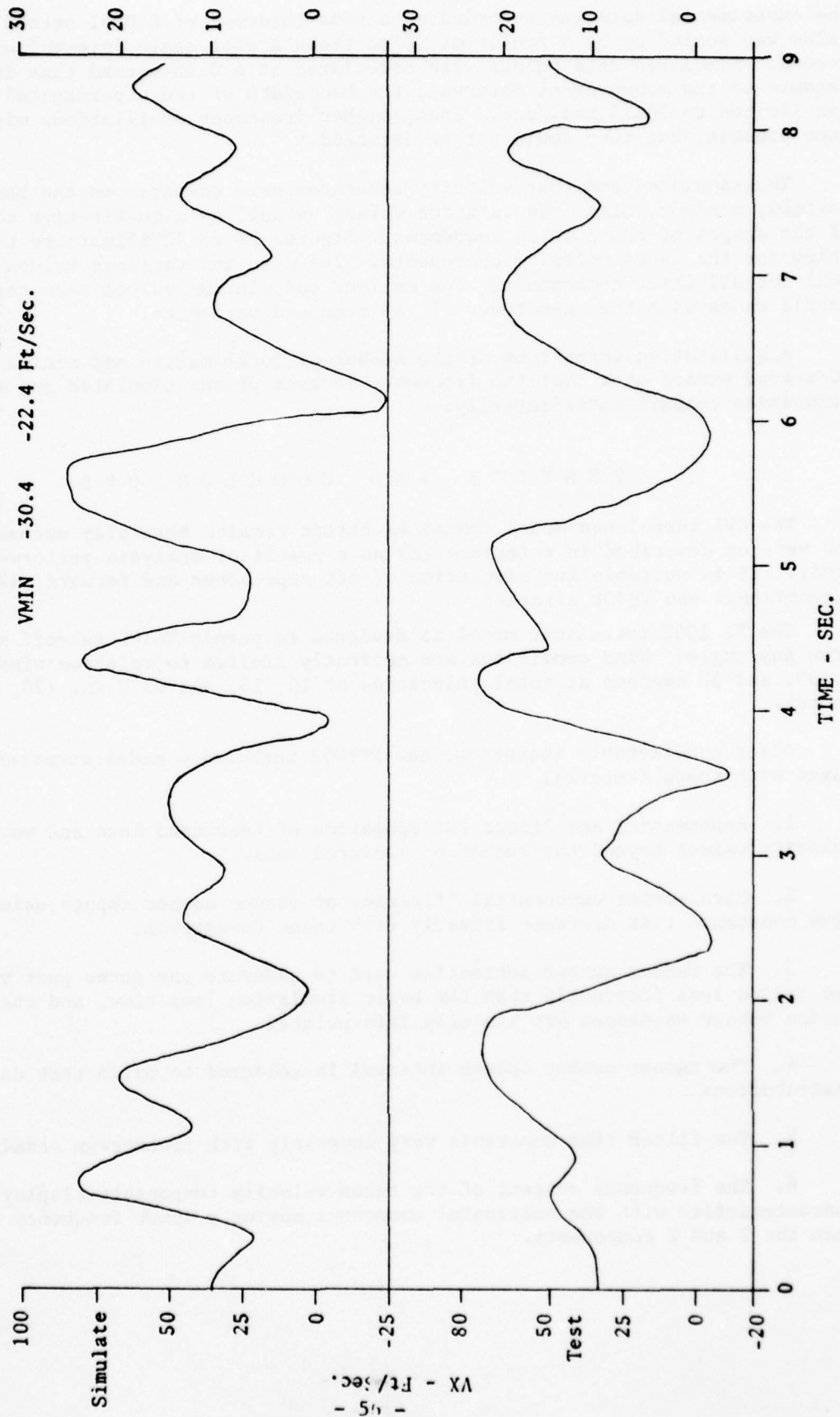
Figure 30 - X - Component Simulated and Measured Turbulence
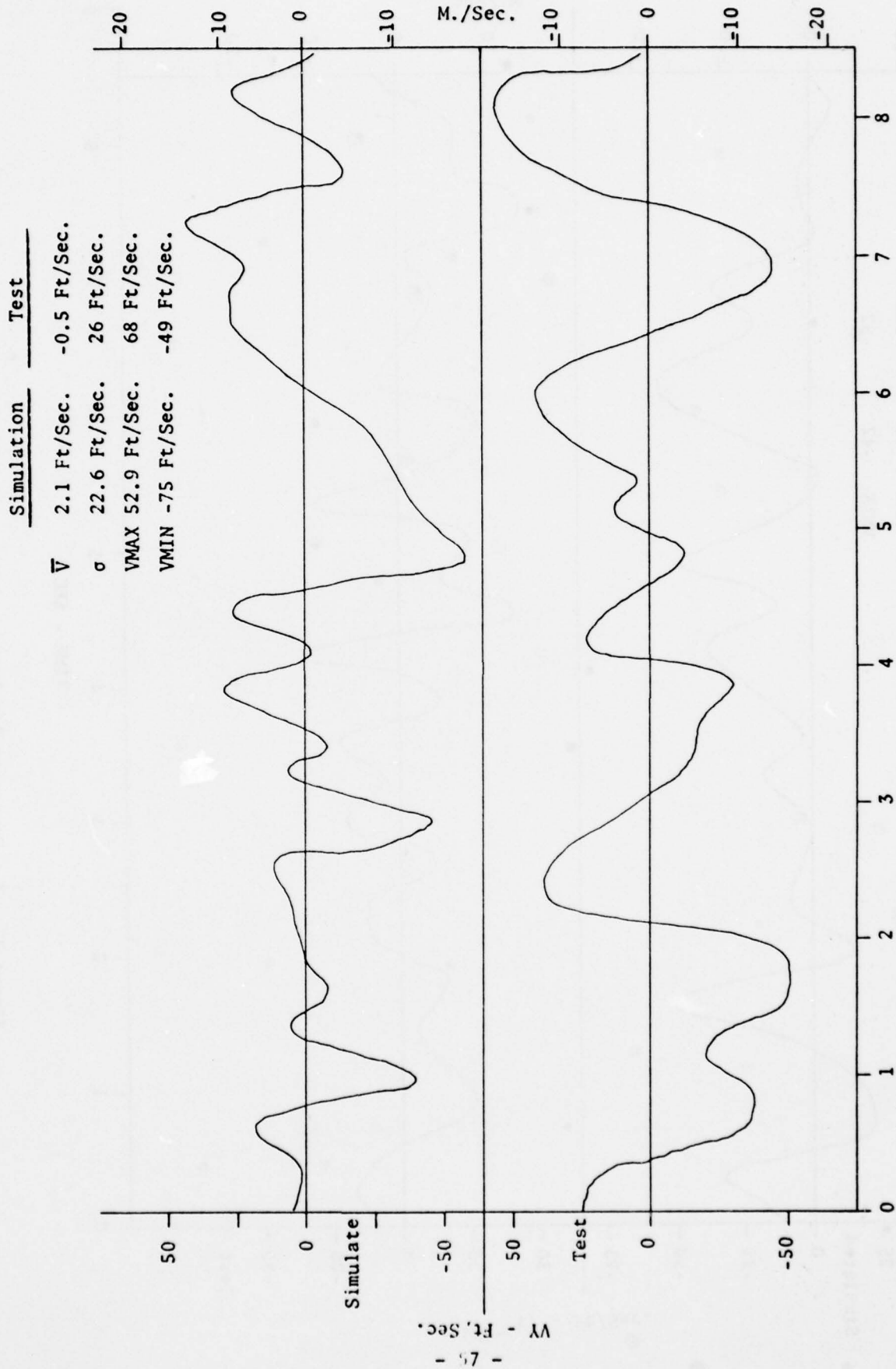
Figure 31 - Y - Component Simulated and Measured Turbulence
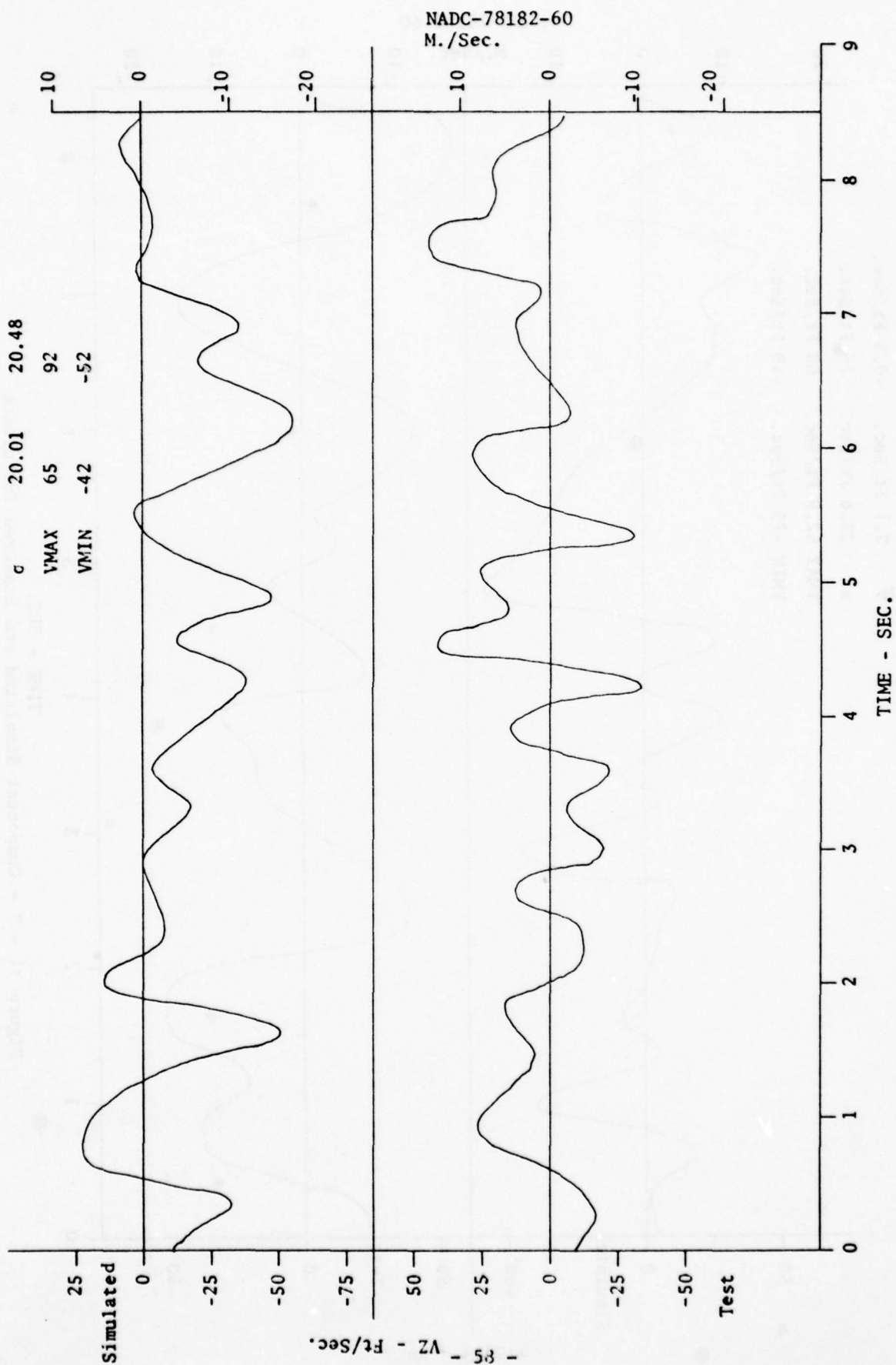
Figure 32 – Z – Component Simulated and Measured Turbulence

- 61 -

7. Although some cross-correlation between velocity components was observed in the measured data, it does not appear significant enough to include in the simulation model.

8. For 45-knot wind and the aircraft located over the deck, the filter frequency parameters were selected with the following values:

Component	Frequency - rad./sec.
X	8.17
Y	10.41
Z	10.00

9. These frequencies decrease linearly to X = 58 M. (190 ft.) where the filter frequencies become

Component	Frequency - rad./sec.
X	1.58
Y	3.0
Z	2.88

10. The test simulation was set up to update wind velocity intervals at 0.05 second intervals. The random number sequences were updated at the following multiple interval size:

Component	Update Interval - Sec.
X	0.05 x 7.12 = 0.356
Y	0.05 x 6.3 = 0.315
Z	0.05 x 6.52 = 0.326

11. Examination of the experimental data shows that the turbulence velocities reasonably approximated a Gaussian distribution. However, the distributions show some flattening and less peaking around the mean than do ideal theoretical distributions.

12. Analysis indicates that it is more important to exactly match the mean and variance of the turbulence velocities than to exactly match the spectral shape.

RECOMMENDATIONS

Because of differences in digital computers and particularly in random number generator subroutines, prospective users of these computer subroutines should follow the following precautions:

1. Run the model repeatedly for at least 100 seconds of simulation time at a fixed location in space.

2. Compare the mean and variance of the simulated data with that of the input tables corresponding to the selected point.

3. Compute the Fourier transform of the simulated turbulence and compare these with the spectral plots contained in this report.

4. Adjust the filter gains, time constants, and number update ratios RNX, RNY, RNZ if necessary.

5. The FF 1052 model should be tested on a moving base piloted simulation to get pilot confirmation of its validity.

L I S T   O F   S Y M B O L S

CVA	Attack Aircraft Carrier
PSIS	Ship Heading – Rad.
PSIREL	Wind Over Deck Relative Angle – Rad.
Rxy	Cross Correlation Function
S	Laplace Operator – 1/Sec.
Sx, y, z	Power Spectral Density
STO	Short Take Off
u	Longitudinal Wind Velocity – M./Sec.
ug	Longitudinal Gust Velocity – M./Sec.
V	Lateral Wind Velocity – M./Sec.
VG	Lateral Gust Velocity – M./Sec.
ν_o	Trim Aircraft Velocity – M./Sec.
VEWBIC	East Component of Natural Wind – M./Sec.
VNWBIC	North Component of Natural Wind – M./Sec.
VW	Total Wind Over Deck – M./Sec.
VS	Ship Speed – M./Sec.
VX	X Component of Wind Velocity – M./Sec.
VY	Y Component of Wind Velocity – M./Sec.
VZ	Z Component of Wind Velocity – M./Sec.
V_∞	Free Stream Wind Velocity – M./Sec.
W	Lateral Wind Velocity – M./Sec.
X	Aircraft Position Aft of Ship – M.
Y	Aircraft Position Left or Right of Ship Centerline – M.
Z	Aircraft Altitude Above Touchdown Point – M.
α	Aircraft Angle of Attack – Deg.
$\dfrac{\Delta u}{VS}$	Normalized Horizontal Velocity Increment
$\dfrac{\Delta w}{VS}$	Normalized Down Wash Velocity Increment
θ	Aircraft Pitch Attitude – Deg.
σ	Root – Mean Squared Value
τ	Gust Time Constant – Sec.
ϕ	Ship Roll Angle – Deg.

$$\phi\frac{\Delta u}{V_0}$$ Horizontal Gust Power Spectrum – $(\text{ft/sec.})^2/(\text{rad/sec.})$

$$\phi\frac{\Delta v}{V_0}$$ Lateral Gust Power Spectrum – $(\text{ft/sec.})^2/(\text{rad/sec.})$

$$\phi\frac{\Delta w}{V_0}$$ Vertical Gust Power Spectrum – $(\text{ft/sec.})^2/(\text{rad/sec.})$

ψ Ship Heading Angle – Deg.

R E F E R E N C E S

a. A Computerized VSTOL/Small Platform Landing Dynamics Investigation Model, Ronald L. Nave, Report No. NADC-77024-30, Naval Air Development Center, Sept 1977.

b. Analysis and Comparison of Carrier Air Wakes, David H. Weir, Report No. TR-NO. 158-1, Systems Technology Inc., April 1966.

c. A Simulator Comparison of an Integrated, Direct-Lift-Control Automatic Carrier Landing System With a Conventional Carrier Landing System, Robert L. Fortenbaugh, Report No. NADC-72210 - VT, Naval Air Development Center, 3 April 1973.

d. Investigation to Study the Aerodynamic Ship Wake Turbulence Generated by a FF 1052 Frigate, Theodore S. Garnett, Jr., Contract No. N00019-75-C-0493 Boeing Vertol Company, December 1976.

e. A Math Model for the Air Wake of a DE-1052 Class Ship, R. L. Fortenbaugh, Report No. 2-53300/7R-3397, Vought Corporation, 13 May 1977.

f. MIL-F-8785 (ASG), Military Specification, Flying Qualities of Piloted Airplanes.

g. Introduction to the Statistical Dynamics of Automatic Control Systems, V. V. Solodovnikov, Dover Publishing.

h. MIL SPEC AR-40A, Automatic Carrier Landing System Airborne Subsystem, General Requirements for.

i. A Wind Tunnel Air Wake Survey of a 1/144 Scale Model Aircraft Carrier With Deck and Island Modifications, Martin L. Cook, Report No. 1805, Naval Ship Research and Development Center, March 1967.

APPENDIX   A

Listing of CVA Turbulence Model

```
       CWINDC
              SUBROUTINE WINDC
              COMMON/XFLOAT/A(500)/IFIXED/IA(200)
              COMMON/CHF/B(200)/ICBF/IB(50)
              COMMON/GAIN1/GA(100)
   5          EQUIVALENCE(T11,A(16)),(T21,A(17)),(T31,A(18))
             1 ,(T12,A(19)),(T22,A(20)),(T32,A(21))
             2 ,(T13,A(22)),(T23,A(23)),(T33,A(24))
              EQUIVALENCE(VNTURB,A(419)),(VETURB,A(420)),(VDTURB,A(421))
              EQUIVALENCE (A(61),UTURB)
  10          EQUIVALENCE (A(62),VTURB)
              EQUIVALENCE (A(63),WTURB)
              EQUIVALENCE (A(70),VRW)
              EQUIVALENCE (A(168),DT)
              EQUIVALENCE (A(238),VEQIC)
  15          EQUIVALENCE(XCG,A(174)),(YCG,A(175)),(STHETR,A(114)),(CTHETR,
             1 A(115))
              EQUIVALENCE(ALT,A(83))
              EQUIVALENCE(A(303),TIME)
              EQUIVALENCE(IA(1),IMODE)
  20          EQUIVALENCF(IONCE,IA(16))
              EQUIVALENCF(VS,B(30))
              EQUIVALENCE(PHIP,B(112))
              EQUIVALENCE(OMEGP,B(111))
              EQUIVALENCF(WGST,B(153)),(VGST,B(154)),(WGST,B(155))
  25          EQUIVALENCF(XFR7,B(156)),(SWHSW,B(157)),(SUBSW,B(158))
              EQUIVALENCF(IH(16),IPITCH)
              EQUIVALENCF(PITCHM,B(110))
              EQUIVALENCE(NCRK,IH(22))
              EQUIVALENCE(B(95),X2S),(B(94),X1S)
  30          EQUIVALENCE(ILTURB,IH(25))
              EQUIVALENCE(IHFRZ,IH(24)),(IWIND,IB(20)),(ILTURB,IH(21))
              EQUIVALENCE(GA(30),GR(1))
              EQUIVALENCE(HIS,B(100))
              EQUIVALENCE(IDISCT,IA(50))
  35          EQUIVALENCE(FRTN,H(194)),(FRTE,B(195)),(FKTO,B(196)),(VMN,B(197))
              EQUIVALENCE(VME,B(198)),(VMD,B(199)),(TDTURB,B(200))
              DIMENSION RO(7),GR(7)
              DIMENSION ROY(7),ROYI(7),IRDST(7),IRDSI(7,10)
              DIMENSION ROX(7)
  40          DATA SWBSW/1./,SUBSW/1./
              DATA TIM3/0./
              DATA(GR(I),I=1,7)/6.,6.,125.,125.,25.,3.,3./
              DATA RUA/.1/
              DATA PI/3.141592/
  45          DATA FC/5./
              DATA (IRDST(I),  I=1,7)/1,3,5,7,9,11,13/
              DATA IUBT/0/,IVHT/0/,IWBT/0/
              DATA ZR1/.001/,ZR2/1.5/,YR1/.001/,YR2/1.5/
              DATA XFR2/1500./
  50          DATA((IRDSI(I,J),J=1,7),I=1,10)/1,3,5,7,9,11,13,1,3,5,7,9,11,
             1 11,13,1,3,5,7,9,11,13,1,3,5,7,9,11,13,13,1,3,5,7,9,11,
             1 13,1,3, 5,7,9,11,13,1,3,5,7,9,11,13,1,3, 5,5,7,9,11,
             3 23,25,25,27,15,17,19,21,23/
  55          IF(IDISCT)7,7,30
```

A - 2

SUBROUTINE WINC

CDC 66   FTN V3.0-P360 OPT=1   76/04/11. 16.03.42.   PAGE   2

```
7       IF(IMODE)2,3,4
2       CONTINUE
        URIS=0.
        WRIS=0.
        WHISS=0.
        UHISS=0.
        PITCHM1=PITCHM/57.3
        DT2=DT
        VO=VEOIC*1.689
        IF(VO.LT.60)VO=60.
        RK10=SQRT(3.14159*5900.)*.003
        RK11=SQRT(5900.*3.14159)*3.*VO/400000.
        S110=-VO/1000.
        S210=-3.*VO/400.
        Z01=EXP(S110*DT)
        Z02=EXP(S210*DT)
        Z11=-1./(S110-S210)*RK10*(1.-Z01)
        Z12=1./(S110-S210)*RK10*(1.-Z02)
        Z13=-1./(S210-S110)*RK11*(1.-Z01)/S110
        Z14=1./(S210-S110)*RK11*(1.-Z02)/S210
        ZO111 =EXP(-VO/100.*DT2)
        ZO111=SQRT(71.63*3.14159)/100.*(1.-ZO111)
        ZO112=EXP(-VO/100.*DT2)
        ZO112=SQRT(200.*3.14159)/100.*(1.-ZO112)
        IX=2**24-3
        DO 10 I=1,7
        RDX(I)=0.
        RDYI(I)=0.
        IF(IONCE.GT.0)  IHDST(I)=IHDSI(I,IONCE)
00010   CONTINUE
        PN1=.044*SQRT(PI)
        WC=2.*FC*PI
        IF(VEOIC.NE.VEOICP)  IZX=1
        VEOICP=VEOIC
3       CONTINUE
        WRSS=0.
        URSS=0.
        UR2S=0.
        PD5P=0.
        PD4=0.
        RD3=0.
        UG=0.
        WG=0.
        WR2S=0.
        UR2SS=0.
        YRSA=0.
        ZRSA=0.
        URSA=0.
        WGSA=0.
        WGSA=0.
        UR2TA=0.
        WR2TA=0.
        WR2SS=0.
        UGSS=0.
        VGI=0.
```

```
      SUBROUTINE WINDC

            VG2=0.
            VG3=0.
            VG4=0.
            VGS=0.
            MGS=0.
            UGSS=0.
            VGSS=0.
            MGSS=0.
            ZRS=0.
            YRS=0.
            ZRSS=0.
            YPSS=0.
            FACY=EXP(-ABS(YCG)/100.)
            ALT1=HIS+50.-XCG*.1
            FACZ=1.
            IF(ALT.GT.ALT1) FACZ=EXP((ALT1-ALT)/50.)
            FACW=FACY*FACZ
            XD=XCG
            UTURH=-VS*SURSW*FACW*TAB1(XD.0..0..68.1)
            WTURH=-VS*SWBSW*FACW*TAB1(XD.0..0..69.1)
            VTURB=0.
            TIM3=0.
            ZR=0.
            YR=0.
            RETURN
    *       CONTINUE
            IF(IWIND.EQ.0)RETURN
            IF(NCHK.GT.0) RETURN
            FACY=EXP(-ABS(YCG)/100.)
            ALT1=HIS+50.-XCG*.1
            FACZ=1.
            IF(ALT.GT.ALT1) FACZ=EXP((ALT1-ALT)/50.)
            FACW=FACY*FACZ
            XD=XCG
            IF(IHFRZ.EQ.1) XD=-XFRZ
            UHSS1=-VS*TAB1(XD.0..0..68.1)
            UHSS=UHSS1*SUHSW*FACW
            IF(ILAURB)21,21,20
00021       WHSS1=-VS*TAB1(XD.0..0..69.1)
            WHSS=WHSS1*SWHSW*FACW
            GO TO 22
00020       WHSS1=VS*TAB1(XD.0..0..70.1)
            WBSS=WBSS1*SWBSW*FACW
00022       CONTINUE
            VSD=1./(.M5*VS)
            CTERM=COSIOMEGP*((1.+(VRW-VS)*VSD)*TIME*XD*VSD*PHIP-1.57))*IPITCH
            UHIK=2.22+.0009*XD
            IF(UH1K.LT.0.0) UB1K=0.0
            UR1=PITCHM1*VS*UHIK*CTERM*FACW
            IF(XCG.LT.-2736.) UB1=0.
            IF(XCG.GT.X2S) UH1=0.
            WB1K=4.98+.001H*XD
            IF(Wd1K.LE.0.0) WB1K=0.0
            WB1=PITCHM1*VS*Wd1K*CTERM*FACW
            IF(XCG.LT.-2536.) WH1=0.
```

```
      SUBROUTINE WINDC
          IF(XCG.GT.X2S) WB1=0.
          SINWCT=SIN(WC*TIME)
          DO 1 I=1,7
110       RDX(I)=U
          CALL RAND(IRDST(I),IX,1,1,U)
          RDY1(I)=RDX(I)-RDYI(I)
          RDYI(I)=RDYI(I)+RDA*RDY(I)*DT
          RD(I)=RDY(I)*SINWCT
       1  CONTINUE
175       SUB2=TAB1(XD,0.,0.,71,1)
          TUB2=TAB1(XD,0.,0.,72,1)
          DTOT=DT/TUB2
          UR2=UR2P*(1.-DTOT)+VS*SUB2*1.414*SQRT(TUB2)*DTOT*RD(1)*GR(1)
          UR2P=UR2
180       DTOTW=DT/3.33
          WH2=WHCP*(1.-DTOTW)+.035*VS*2.58*DTOTW*RD(2)*GK(2)
          IF(XD.LT.-2540.) WB2=0.
          IF(XD.GT.X1S) WH2=0.
          WR2P=WH2
185       VYBR=WB2
          VXBR=UBSS+UR1+UR2
          VDBR=WBSS+WB1+WB2
          VNAR=VXBR*CTHETR-VYBR*STHETR
          VERR=VYBR*CTHETR+VXBR*STHETR
190       UHT=T11*VNAR+T12*VEBR+T13*VDBR
          VBT=T21*VNAR+T22*VEBR+T23*VDBR
          WHT=T31*VNAR+T32*VEBR+T33*VDBR
          IF(IU4T.EQ.1) UBT=0.
          IF(IVHT.EQ.1) VUT=0.
195       IF(IHBT.EQ.1)WBT=0.
          WG=ZO1l1*WG+ZI111*RD3
          RD3=RD(3)*GR(3)
          UG=ZO112*UG+ZI112*RD4
          RD4=RD(4)*GR(4)
200       VG1=ZO1*VG1+ZI1*RD5P
          VG2=ZO2*VG2+ZI2*RD5P
          VG3=ZO1*VG3+ZI3*RD5P
          VG4=ZO2*VG4+ZI4*RD5P
          RD5P=RD(5)*GR(5)
205       VG=VG1+VG2+VG3+VG4
          IF(ILTURB.EQ.1) GO TO 5
          UG=0.0
          VG=0.
          WG=0.
210    5  CONTINUE
          UTURB=UBT+UG
          VTURB=VBT+VG
          WTURB=WBT+WG
          ZR=RN1*RD(6)*GR(6)*(ZR1*ABS(XD)+ZR2)
215       YR=RN1*RD(7)*GR(7)*(YR1*ABS(XD)+YR2)
          UH1S=UH1S+UA1
          WH1S=WH1S+WB1
          UH2S=UR2S+UH2
          WB2S=WH2S+WR2
220       UB1SS=UB1SS+DT*UB1**2
```

```
        SUBROUTINE WINDC

              WB1SS=WB1SS+DT*WH1**2
              UB2SS=UB2SS+DT*UB2**2
              WR2SS=WB2SS+DT*WB2**2
              UGS=UGS+UG
 225          VGS=VGS+VG
              WGS=WGS+WG
              UGSS=UGSS+DT*UG**2
              VGSS=VGSS+DT*VG**2
              WGSS=WGSS+DT*WG**2
 230          ZRS=ZRS+ZR
              YRS=YRS+YR
              ZPSS=ZRSS+DT*ZR**2
              YPSS=YRSS+DT*YR**2
              IF(ITIME)  30,30,25
 235  00025   CONTINUE
              PAV=TIME/DT
              UB1A=UB1S/RAV
              WR1A=WR1S/RAV
              YRSA=YRS/RAV
 240          ZRSA=ZRS/RAV
              UGSA=UGS/RAV
              VGSA=VGS/RAV
              WGSA=WGS/RAV
              UH2TA=UB2S/RAV
 245          WR2TA=WH2S/RAV
              UB2ST=UB2SS/TIME
              WR2ST=WB2SS/TIME
              UGST=UGSS/TIME
              VGST=VGSS/TIME
 250          WGST=WGSS/TIME
              ZRST=ZRSS/TIME
              YRST=YRSS/TIME
              UP1ST=UB1SS/TIME
              WH1ST=WH1SS/TIME
 255  00030   CONTINUE
              IF(IDISCT)37,37,33
       33     CONTINUE
              FRT=AMAX1(FRTN,FHTE,FRTD)
              PHASE=FRT*(TIME-TDTURB)
 260          IF(PHASE-6.28)34,34,36
       34     IF(TIME-TDTURB)36,36,35
       35     VNTURB=.5*VMN*(1.-COS(FRTN*(TIME-TDTURB))  )
              VETURH=.5*VME*(1.-COS(FRTE*(TIME-TDTURB))  )
              VDTURH=.5*VMD*(1.-COS(FRTD*(TIME-TDTURH))  )
              GO TO 37
 265   36     VNTURB=0.
              VETURH=0.
              VDTURH=0.
       37     CONTINUE
              RETURN
 270          END
```

SUBROUTINE WINDC

SYMBOLIC REFERENCE MAP

ENTRY POINTS   DEF LINE   REFERENCES
1 WINDC   2   135   137   138   270

VARIABLES	SN	TYPE	RELOCATION								
0	A	REAL	ARRAY XFLOAT	REFS	3	9*6	3*9	10	11	12	13
122	ALT	REAL	XFLOAT	14	15	4*15	18	19			
1143	ALT1	REAL		REFS	18	2*126	2*126	2*142	124	140	
0	B	REAL	ARRAY CBF	REFS	4	2*142	2*142	DEFINED	24	3*25	3*26	28
				2*30	34	4*36	3*37				
1159	CTERM	REAL		REFS	159	164	DEFINED	156			
152	CTHETA	REAL	XFLOAT	REFS	16	188	189	71	177	180	
247	DT	REAL	XFLOAT	REFS	14	63	70	227	226	229	232
				221	222	223					
				236							
1165	DTOT	REAL		REFS	2*178	DEFINED	177				
1170	DTOTW	REAL		REFS	2*181	DEFINED	180				
1055	DT2	REAL		REFS	76	78	DEFINED	63			
1145	FACW	REAL		REFS	129	130	147	150	153	159	164
				DEFINED	127	143					
11-2	FACY	REAL		REFS	127	143	DEFINED	123	139	141	142
11-4	FACZ	REAL		REFS	127	143	DEFINED	125	126		
751	FC	REAL		REFS	87	46					
1216	FRT	REAL	CBF	REFS	259	DEFINED	258				
303	FRTD	REAL	CBF	REFS	36	258	264				
302	FRTE	REAL	C3F	REFS	36	258	263				
301	FRTN	REAL		REFS	36	258	262				
0	GA	REAL	ARRAY GAIN1	REFS	5	33	178	181	197	199	204
35	GP	REAL	ARRAY GAIN1	REFS	33	38	43				
143	HIS	REAL		REFS	34	DEFINED	140				
1076	I	INTEGER	CBF	REFS	82	83	2*84	169	170	3*171	3*172
				2*173	DEFINED	81	168				
0	IA	INTEGER	ARRAY IFIXED	REFS	3	20	35	29	31	3*32	
0	IB	INTEGER	ARRAY ICBF	REFS	4	21	27				
27	IHFRZ	INTEGER	ICBF	REFS	32	145					
51	IDISCT	INTEGER	IFIXED	REFS	35	55	256				
30	ILBURR	INTEGER	ICBF	REFS	31	148					
24	ILTURB	INTEGER	ICBF	REFS	32	206					
0	IMODF	INTEGER	IFIXED	REFS	20	56					
17	IOUNCE	INTEGER	ICBF	REFS	21	2*84					
21	IPITCH	INTEGER	ICBF	REFS	27	156					
1234	IKDSI	INTEGER	ARRAY	REFS	39	84	DEFINED	51			
1245	IRDST	INTEGER	ARRAY	REFS	39	169	DEFINED	47			
752	IUBT	INTEGER		REFS	193	DEFINED	48	84			
753	IVBT	INTEGER		REFS	194	DEFINED	48				
764	IWBT	INTEGER		REFS	195	DEFINED	48				
23	IWIND	INTEGER	ICBF	REFS	32	137					
1075	IX	INTEGER		REFS	169	DEFINED	80				
1132	IZX	• INTEGER		DEFINED							
25	NCHK	INTEGER	ICBF	REFS	29	138					
156	OMEGP	REAL	CBF	REFS	24	156					

A-7

`CDC 6500 FTN V3.0-P380 OPT=1   78/04/11. 16.03.42.`

SUBROUTINE WINDC

VARIABLES	SN	TYPE	RELOCATION							
1217 PHASE		REAL		REFS	260	DEFINED	259			
157 PHIP		REAL		REFS	23	156				
760 PI		REAL	CHF	REFS	86	87	DEFINED	45		
155 PITCHM		REAL		REFS	28	62	DEFINED			
1054 PITCHM1		REAL	CBF	REFS	159	164	DEFINED	62		
1204 RAV		REAL		REFS	237	238	239	240	241	242	243
				244	245	236				
1220 RD		REAL	ARRAY	REFS	38	178	DEFINED	141	197	199	204	214
				215	DEFINED	173				
757 RDA		REAL		REFS	172	DEFINED	44			
1362 RDX		REAL	ARRAY	REFS	40	171	DEFINED	170		
1227 RDY		REAL	ARRAY	REFS	39	172	173	171		
1236 RDYI		REAL	ARRAY	REFS	39	171	DEFINED	83	172	
1110 RD3		REAL		REFS	196	197	96			
1107 RD4		REAL		REFS	198	199	95			
1106 RD5P		REAL		REFS	200	201	203	202	DEFINED	94	206
1057 RK10		REAL		REFS	72	73	66	DEFINED		
1050 RK11		REAL		PEFS	74	75	67	DEFINED		
1077 RN1		REAL		REFS	214	215	86	DEFINED		
161 SIN#CT		REAL		REFS	173	DEFINED	157			
161 STHETR		REAL		REFS	16	188	189			
235 SUBSW		REAL	XFLOAT	REFS	26	129	147	DEFINED	41	41
1163 SUB2		REAL	CBF	REFS	178	172	175			
234 SWBSW		REAL	CBF	REFS	26	130	150	DEFINED	75	
1061 S110		REAL		REFS	70	72	73	2*74	2*75	
1062 S210		REAL		DEFINED	68	71	74	2*75		
				REFS	71	72	73			
307 TDTURB		REAL	CBF	DEFINED	63					
456 TIME		REAL	XFLOAT	REFS	37	259	261	262	263	264
				REFS	19	156	167	234	236	246
				248	250	251	252	253	254
				261	262	263	264			
770 TIM3		REAL		DEFINED	42	132				
104 TUB2		REAL		REFS	177	178	DEFINED	176		
17 T11		REAL	XFLOAT	REFS	6	190				
22 T12		REAL	XFLOAT	REFS	6	190				
25 T13		REAL	XFLOAT	REFS	6	190				
20 T21		REAL	XFLOAT	REFS	6	191				
23 T22		REAL	XFLOAT	REFS	6	191				
26 T23		REAL	XFLOAT	REFS	6	191				
21 T31		REAL	XFLOAT	REFS	6	192				
24 T32		REAL	XFLOAT	REFS	6	192				
27 T33		REAL	XFLOAT	REFS	6	192				
152 U		REAL		REFS	169	170				
1104 UBSS		REAL		REFS	186	DEFINED	92	147		
1151 UBSS1		REAL		REFS	147	DEFINED	146			
1200 UBT		REAL		REFS	211	DEFINED	190	193		
1136 UB1		REAL		REFS	186	216	220	DEFINED	159	160	161
1205 UB1A	*	REAL		DEFINED	237					
1165 UB1K		REAL		REFS	158	159	DEFINED	157	158	
1030 UB1S		REAL		REFS	216	237	DEFINED	58	216	
1033 UB1SS		REAL		REFS	220	253	DEFINED	61	220	
1214 UB1ST	*	REAL		DEFINED	253					
1166 UB2		REAL		REFS	179	186	218	DEFINED	178	222	

CDC 6600 FTN V3.0-P380 OPT=1   74/04/11. 16.03.42.   PAGE   8

SUBROUTINE WINDC

VARIABLES	SN	TYPE	RELOCATION						
1167 UB2P		REAL		REFS 178	DEFINED 179				
1105 UB2S		REAL		REFS 218	244	DEFINED 93	218		
1114 UB2SS		REAL		REFS 222	246	DEFINED 100	222		
1210 UR2ST	•	REAL		DEFINED 246					
1121 UB2TA		REAL		DEFINED 106	244				
1111 UG		REAL		REFS 198	211	224	DEFINED 227	97	198
				207					
1124 UGS		REAL		REFS 224	241	DEFINED 109			
1117 UGSA		REAL		DEFINED 103	241				
1133 UGSS		REAL		REFS 227	248	116	227		
230 UGST		REAL	CBF	REFS 25	DEFINED 248				
74 UTURB		REAL	XFLOAT	REFS 10	129	211			
1201 VBT		REAL		REFS 212	191	194			
1175 VDBR		REAL		REFS 190	192	DEFINED 268	187		
644 VCTURB		REAL	XFLOAT	REFS 9	264				
1177 VEBP		REAL		REFS 190	191	192	DEFINED 89	189	
355 VEUIC		REAL	XFLOAT	REFS 15	64	88			
1101 VEUICP		REAL		REFS 88	89				
643 VETURB		REAL	XFLOAT	REFS 9	263	267			
1203 VG		REAL		REFS 212	225	228	DEFINED 114	205	208
1121 VGS		REAL		REFS 242	242		225		
1207 VGSA		REAL	•	DEFINED 228	249	DEFINED 117	228		
1434 VGSS		REAL		REFS 228	249				
231 VGST		REAL	CBF	REFS 25					
1125 VG1		REAL		REFS 200	205	DEFINED 110	200		
1126 VG2		REAL		REFS 201	205	DEFINED 111	201		
1127 VG3		REAL		REFS 202	205	DEFINED 112	202		
1110 VG4		REAL		REFS 203	205	DEFINED 113	203		
305 VMD		REAL	CBF	REFS 37	264				
305 VME		REAL	CBF	REFS 37	263				
304 VMN		REAL	CBF	REFS 36	262				
1176 VNPR		REAL		REFS 190	191	192	188		
642 VNTUPB		REAL	XFLOAT	DEFINED 9	262	266			
1056 VO		REAL		REFS 65	67	68	69	76	78
105 VRW		REAL	XFLOAT	DEFINED 64	65				
35 VS		REAL	CBF	REFS 13	129	130	146	149	152	155
				156					
1153 VSD		REAL		REFS 22	164	178	181		
75 VTURB		REAL		159	155				
1174 VXBR		REAL	XFLOAT	REFS 2n15b	11	DEFINED 131	212		
1173 VYBR		REAL		REFS 188	189	DEFINED 186	185		
1103 WHSS		REAL		REFS 188	189	150			
1152 WHSS1		REAL		REFS 187	DEFINED 91	149	152		
1202 WRT		REAL		REFS 150	153	DEFINED 195	153		
1160 WR1		REAL		REFS 213	192	221	DEFINED 164	165	166
1206 WB1A	•	REAL		DEFINED 187					
1157 WB1K		REAL		REFS 238	164	DEFINED 162	163		
1051 WB1S		REAL		REFS 163	238	DEFINED 59	217		
1052 WHISS		REAL		REFS 217	254	DEFINED 60	221		
1215 WB1ST	•	REAL	XFLOAT	DEFINED 254					
1171 WB2		REAL		REFS 184	185	187	219	223	
				DEFINED 181	182	183			
1172 WB2P		REAL		REFS 181	184				

CDC 6600 FTN V3.0-P380 OPT=1   78/04/11. 16.03.42.   PAGE 9

SUBROUTINE WINDC

VARIABLES	SN	TYPE	RELOCATION								
1113 WM2S		REAL		REFS	219	245	DEFINED	99	219		
1123 WM2SS		REAL		REFS	223	247	DEFINED	108	223		
1211 WM2ST	•	REAL		DEFINED	247						
1122 WM2TA		REAL		DEFINED	107	245					
1100 WC		REAL		REFS	167	DEFINED	87	DEFINED	98		
1112 WG		REAL		REFS	196	226	229	DEFINED	196		
				209							
1132 WGS		REAL		REFS	226	243	115	226			
1120 WGSA		REAL		DEFINED	104	105					
1135 WGSS		REAL		REFS	229	250	118	224			
232 WGST		REAL		REFS	25	DEFINED	250	213			
76 WTURB		REAL	CBF	REFS	12	DEFINED	130				
255 XCG		REAL	XFLOAT	REFS	16	128	140	144	160	161	
			XFLOAT	165	124						
1146 XD		REAL		REFS	129	130	149	152	156	157	
				162	176	182	183	214	215		
				128	144	145					
233 XFRZ		REAL	CBF	DEFINED	145	DEFINED	50				
135 X1S		REAL	CBF	REFS	26	183					
136 X2S		REAL	CBF	REFS	30	161	166				
255 YCG		REAL	XFLOAT	REFS	16	123	139				
1150 YH		REAL		REFS	231	233	DEFINED	134	215		
1137 YRS		REAL		REFS	231	239	DEFINED	120	231		
1115 YRSA		REAL		DEFINED	101	239					
1141 YRSS		REAL		REFS	233	252	122	233			
1213 YRST	•	REAL		DEFINED	252	DEFINED					
767 YP1		REAL		REFS	215	DEFINED	49				
770 YR2		REAL		REFS	200	DEFINED	49				
1065 Z11		REAL		REFS	200	DEFINED	72				
1072 Z111		REAL		REFS	196	DEFINED	77				
1074 Z1112		REAL		REFS	198	DEFINED	79				
1062 Z12		REAL		REFS	201	DEFINED	73				
1067 Z13		REAL		REFS	202	DEFINED	74				
1070 Z14		REAL		REFS	203	DEFINED	75				
1063 Z01		REAL		REFS	72	200	202	DEFINED	70		
1071 Z0111		REAL		REFS	77	DEFINED	76				
1073 Z0112		REAL		REFS	79	DEFINED	78				
1064 Z02		REAL		REFS	73	201	203	DEFINED	71		
147 ZR		REAL		REFS	230	232	DEFINED	133	214		
1136 ZRS		REAL		REFS	230	DEFINED	119	230			
1116 ZRSA		REAL		DEFINED	102	240					
1140 ZRSS		REAL		REFS	232	251	121	232			
1212 ZRST	•	REAL		DEFINED	251	DEFINED					
765 ZR1		REAL		REFS	214	DEFINED	49				
765 ZR2		REAL		REFS	214	DEFINED	49				

EXTERNALS		TYPE	ARGS	REFERENCES				
COS		REAL	1 LIBRARY	156	262	263	264	
EXP		REAL	1 LIBRARY	70	71	76	78	123	139	142
RAND			5	169				
SIN		REAL	1 LIBRARY	167	66	67	77	79	86	126
SQRT		REAL	1 LIBRARY	66	178	175		
TAH1		REAL	5	129	130	146	149	152	176

A - 10

A P P E N D I X   B

Definition of Variables Used in CVA Program

A	Common Array
alt	Aircraft Altitude Above Sea Level - Ft.
alt_1	Altitude Boundary on Turbulence - Ft.
B	Common Storage Array
CTERM	Periodic Amplitude of Sinusoidal Airwake Terms
DT	Time Increment - Sec.
DTOT	Nondimensionalized Time Increment of u Burble Component
DTOTW	Nondimensionalized Time Constant of W Burble Component
DT2	Time Increment - Second
FacW	Extrapolation Factor of Airwake Velocity
FacY	Extrapolation Function in Y Direction
FacZ	Extrapolation Function in Z Direction
FC	Shift Frequency - Cycle/Sec.
FRT	Maximum Gust Frequency - Rad./Sec.
FRTD	Frequency of Vertical Discrete Gust - Rad./Sec.
FRTE	Frequency of East Discrete Gust - Rad./Sec.
FRTN	Frequency of North Discrete Gust - Rad./Sec.
GA	Common Storage Array
GR	Array Containing Turbulence Gains
HIS	Steady Deck Height Above Sea Level - Ft.
I	Integer Counter
Ia	Integer Common Array
IB	Integer Common Array
IBFRZ	Constant Range Flag
IDISCT	Discrete Turbulence Flag
ILBURB	Downwash Selection Switch
ILTURB	Free Air Turbulence Switch
IMode	Operating Mode Switch
Ionce	Turbulence Initialization Option Switch
IPitch	Ship Pitch Flag
IRDSI	Start Up Array

IRDST	Start Up Array
IuBT	Switch for u Burble Component
IVBT	Switch for V Burble Component
IWBT	Switch for W Burble Component
Iwind	Turbulence Selection Switch
IX	Random Number Startup Parameter
OMEGP	Ship Pitch Frequency - Rad/Sec.
Phase	Discrete Turbulence Phase - Rad.
PHIP	Ship Pitch Phase - Rad.
PI	3.14159
PITCHM	Ship Pitch Magnitude - Deg.
PITCHMI	Ship Pitch Magnitude - Rad.
RAV	Averaging Parameter
RD	Filtered Output of Random Number Generator
RDA	Time Constant of Random Number Filter - 1/Sec.
RDX	Raw Output of Random Number Generator
RDY	Intermediate Random Number Value
RDYI	Intermediate Random Number Value
RD3	Intermediate Turbulence Variable
RD4	Intermediate Turbulence Variable
RD5P	Intermediate Turbulence Variable
RK10	Turbulence Filter Gain
RN1	Radar Noise Gain
SIN WCT	Frequency Shifting Function
STHETR	Sine of Ship Heading Angle
SuBSW	Steady u Burble Scale Factor
SuB2	Random u Burble RMS Magnitude
SwBSW	Steady w Burble Scale Factor
S110	Filter Parameter
S210	Filter Parameter
TDTURB	Discrete Turbulence Switch Time - Sec.
TIME	Simulation Running Time - Sec.
TuB2	Random u Burble Time Constant - Sec.
T11 - T33	Euler Angle Conversion Matrix Relating Aircraft Body Axes and Inertial Axes
u	Output of Random Number Generator

uBSS	Steady u Component of Burble - Ft./Sec.
UBSS1	Intermediate Turbulence Variable
UBT	u-Body Axis Burble Component - Ft./Sec.
uB1	X-Ship Axis Periodic Burble - Ft./Sec.
uB1A	Intermediate Variable
uB1K	Intermediate Variable
uB1S	Statistical Summary Variable
uB1SS	Statistical Summary Variable
uB1ST	Statistical Summary Variable
uB2	Ship X Axis Random Burble Component - Ft./Sec.
uB2P	Intermediate Variable
uB2S	Statistical Summary Variable
uB2SS	Statistical Summary Variable
uB2ST	Statistical Summary Variable
uB2TA	Statistical Summary Variable
uG	Aircraft X-Axis Free Air Turbulence Component - Ft./Sec.
uGS	Statistical Summary Variable
uGSA	Statistical Summary Variable
uGSS	Statistical Summary Variable
uGST	Statistical Summary Variable
uTURB	Total Aircraft X-Axis Turbulence - Ft./Sec.
VBT	Lateral Burble Velocity - Ft./Sec.
VDBR	Vertical Burble Component - Ft./Sec.
VDTURB	Vertical Turbulence Velocity - Ft./Sec.
VEBR	East Component of Burble - Ft./Sec.
VEQIC	Aircraft Trim Velocity - Knots
VEQICP	Previous Trim Velocity - Knots
VETURB	East Component of Turbulence - Ft./Sec.
VG	Aircraft Y-Axis Component of Free Air Turbulence - Ft./Sec.
VGS	Statistical Summary Variable
VGSA	Statistical Summary Variable
VGSS	Statistical Summary Variable
VGST	Statistical Summary Variable
VG1	Intermediate Variable
VG2	Intermediate Variable
VG3	Intermediate Variable

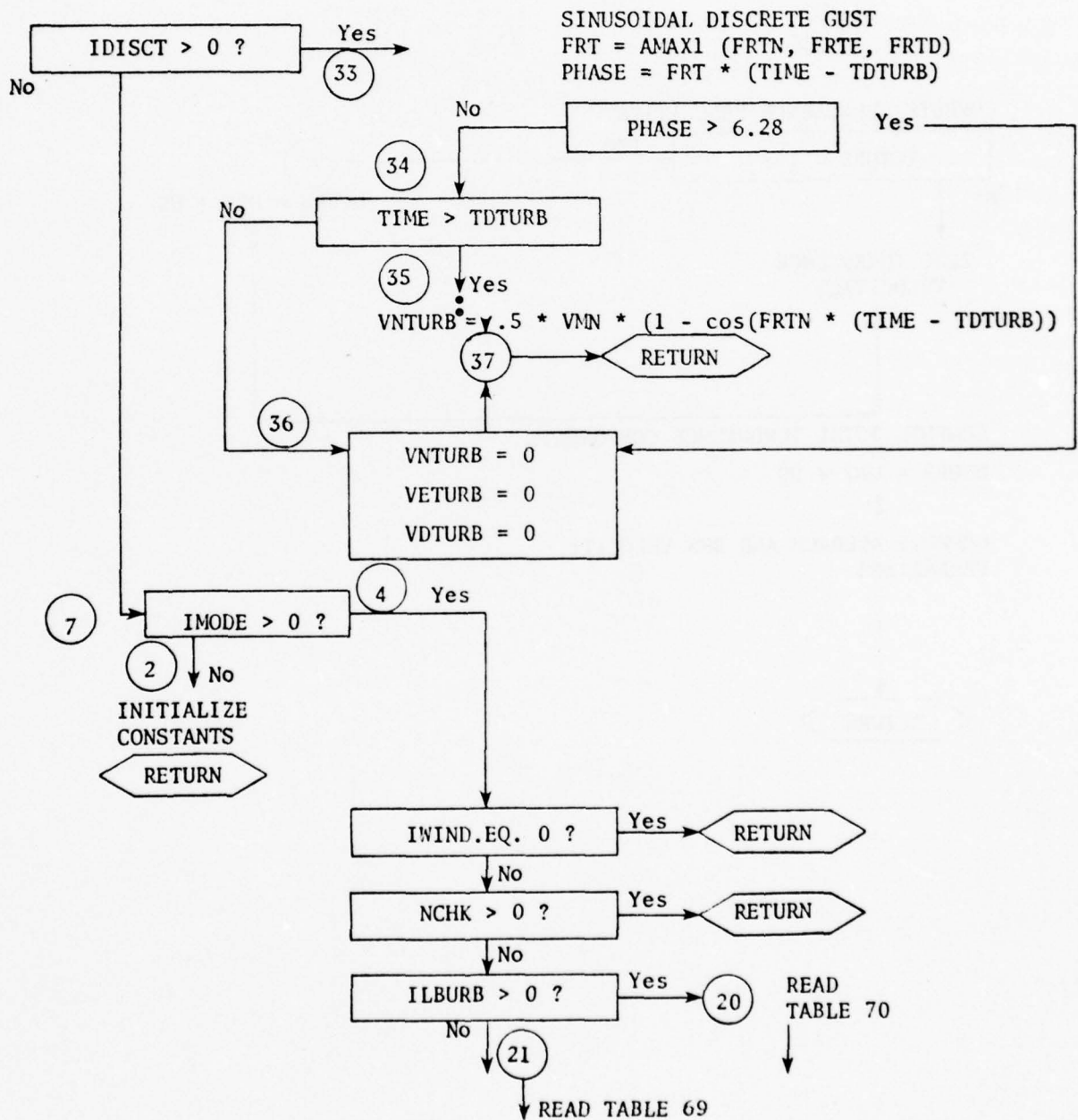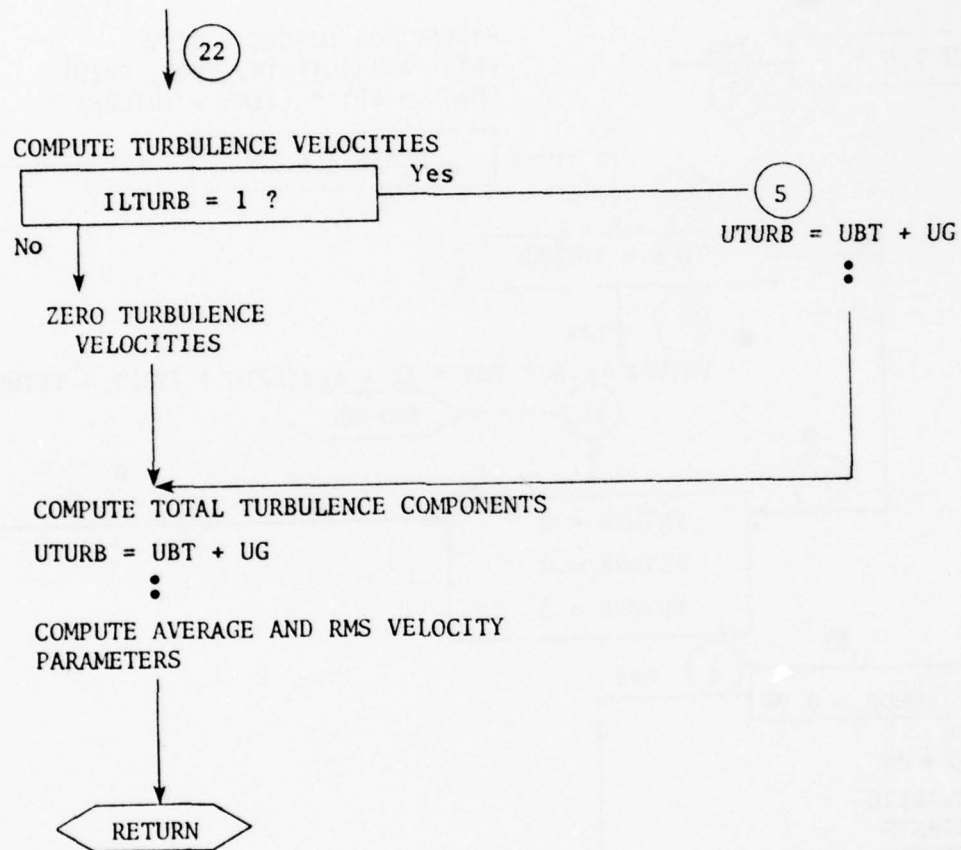| VG4	Intermediate Variable
VMD	Vertical Discrete Gust Magnitude - Ft./Sec.
VME	East Discrete Gust Magnitude - Ft./Sec.
VMN	North Discrete Gust Magnitude - Ft./Sec.
VNBR	North Burble Component - Ft./Sec.
VNTURB	North Turbulence Component - Ft./Sec.
VO	Trim Velocity - Ft./Sec.
VRW	Aircraft Airspeed - Ft./Sec.
VS	Relative Wind Over Deck Speed - Ft./Sec.
VSD	Burble Propagation Speed - Ft./Sec.
VTURB	Aircraft Y Axis Component of Total Turbulence - Ft./Sec.
VXBR	Ship X Axis Component of Burble - Ft./Sec.
VYBR	Ship Y Axis Component of Burble - Ft./Sec.
WBSS	Steady Downwash Velocity - Ft./Sec.
WBSS1	Intermediate Variable
WBT	Aircraft Z Axis Component of Burble - Ft./Sec.
WB1	Periodic Component of Ship Downwash - Ft./Sec.
WB1A	Statistical Summary Variable - Ft./Sec.
WB1K	Intermediate Variable
WB1S	Statistical Summary Variable
WB1SS	Statistical Summary Variable
WB1ST	Statistical Summary Variable
WB2	Vertical Random Burble Component - Ft./Sec.
WB2P	Intermediate Variable
WB2S	Statistical Summary Variable
WB2SS	Statistical Summary Variable
WB2ST	Statistical Summary Variable
WB2TA	Statistical Summary Variable
WC	Frequency Shift Parameter - Rad./Sec.
WG	Aircraft Z-Axis Free Air Turbulence
WGS	Statistical Summary Variable
WGSA	Statistical Summary Variable
WGSS	Statistical Summary Variable
WGST	Statistical Summary Variable
WTURB	Aircraft Z-Axis Turbulence Velocity - Ft./Sec.
XCG	Aircraft X Position Relative to Ship cg - Ft.

XD	X-Position Variable Used in Table Look Up – Ft.
XFRZ	Fixed Position Used in Table Look Up – Ft.
X1S	Forward Turbulence Limit – Ft.
X2S	Forward Turbulence Limit – Ft.
YCG	Aircraft Lateral Position Relative to Ship – Ft.
YR	Lateral Radar Error – Ft.
YRS	Statistical Summary Variable
YRSA	Statistical Summary Variable
YRSS	Statistical Summary Variable
YRST	Statistical Summary Variable
YR1	Scale Factor on Radar Noise Function
YR2	Scale Factor on Radar Noise Function
ZI1	Turbulence Filter Parameters
ZI111	Turbulence Filter Parameters
ZI112	Turbulence Filter Parameters
ZI2	Turbulence Filter Parameters
ZI3	Turbulence Filter Parameters
ZI4	Turbulence Filter Parameters
ZO1	Turbulence Filter Parameters
ZO111	Turbulence Filter Parameters
ZO112	Turbulence Filter Parameters
ZO2	Turbulence Filter Parameters
ZR	Vertical Radar Noise – Ft.
ZRS	Statistical Summary Parameter
ZRSA	Statistical Summary Parameter
ZRSS	Statistical Summary Parameter
ZRST	Statistical Summary Parameter
ZR1	Radar Noise Parameter
ZR2	Radar Noise Parameter

A P P E N D I X   C

Flow Chart for CVA Model

SINUSOIDAL DISCRETE GUST
FRT = AMAX1 (FRTN, FRTE, FRTD)
PHASE = FRT * (TIME - TDTURB)

IDISCT > 0 ? —Yes→ (33)

No

PHASE > 6.28 No / Yes

(34)

TIME > TDTURB No

(35) Yes

$$VNTURB = .5 * VMN * (1 - cos(FRTN * (TIME - TDTURB)))$$

(37) → RETURN

(36)

VNTURB = 0
VETURB = 0
VDTURB = 0

(7) (4) Yes

IMODE > 0 ?

(2) No

INITIALIZE
CONSTANTS

RETURN

IWIND.EQ. 0 ? —Yes→ RETURN

No

NCHK > 0 ? —Yes→ RETURN

No

ILBURB > 0 ? —Yes→ (20) READ TABLE 70

No (21)

READ TABLE 69

COMPUTE TURBULENCE VELOCITIES

```
┌─────────────────────────┐   Yes
│     ILTURB = 1 ?        │ ──────────────────────────────►  (5)
└─────────────────────────┘                                  UTURB = UBT + UG
  │ No                                                              ⋮
  ▼
ZERO TURBULENCE
   VELOCITIES
  │
  ▼
```

COMPUTE TOTAL TURBULENCE COMPONENTS

UTURB = UBT + UG
⋮

COMPUTE AVERAGE AND RMS VELOCITY
PARAMETERS

⟨ RETURN ⟩

APPENDIX   D

Listing of FF 1052 Turbulence Subroutine

SUBROUTINE WINDC   74/74   OPT=1   FTN 4.5+428   79/01/15. 08.01.01   PAGE   1

```
                SUBROUTINE WINDC
                COMMON/XFLCAT/A(500)/IFIXED/IA(200)
                COMMON/CHF/A(200)/IC4F/IA(50)
5               EQUIVALENCE (ALT,A(H3)),(IA(1),IMODE),(VS,B(30)),(DT,A(164)),
               1(VS,A(76)),(CVS,A(77)),(VDS,A(78)),(A(419),VATUR4),(A(420),VETUR4
               2),(A(465),VATUR4)),(VDS+IC,B(35)),(VEWHIC,B(35)),(PSIS,B(34)))
                EQUIVALENCE (KF,A(141)),(KF,B(142))
                EQUIVALENCE (A(600),DSTW)
10              EQUIVALENCE (DTD,B(103))
                EQUIVALENCE (TA140,IA(200)
                EQUIVALENCE (TIME,A(303)),(IOMCE,IR(16))
                DATA IOMCE/1/
                DATA REAN/46.76/,RLTD/351./,RLS/441./
15              DATA IHDSTX/37/,IHDSTY/43/,IHDSTZ/53/,PI/3.14159/
                DATA IHDSTXT/37/,IHDSTYI/43/,IHDSTZI/53/
                DATA REX/7.12/,WVY/5.3/,2N2/6.52/
                DATA SLOPEX/.00133333/
                TF(IMODE)17,16,20
        C       INITIALIZE VELOCITIES AND RANDOM NUMBER GENERATORS
        15      VATUR4=0.
                VETUR4=0.
20              VTTUR4=0.
                RETURN
        20      IF(IMODE)1,1,2
        1       IY=2524-3
                SLOPE1=0.
                VXT=0.
                VYT=0.
                VXTA=0.
30              VYTA=0.
                VZT=0.
                TCCOUNT=0.
                TCCOUNTY=0.
                TCCOUNTZ=0.
35              DEROXT=0.
                RANDYR=0.
                RANDZR=0.
                IF(IOMCE.LT.1) GO TO 21
40              IHDSTYI=IHDSTX
                IHDSTYI=IHDSTY
                IHDSTZI=IHDSTZ
        21      CONTINUE
                TCOUNT=0.
        C       SET DTX TO CONSTANT SO THAT TURBULENCE SEQUENCE REMAINS CONSTANT
        C       REGARDLESS OF LOOP TIME USED IN AIRCRAFT SIMULATION
                DTX=.05
                IF(DT.GT..05)DTX=DT
        C       COMPUTE TIME INCREMENTS FOR RANDOM NUMBER GENERATORS
50              DTX=DTX*RLX
                DTY=DTX*WVY
                DTZ=DTX*RLZ
                PSISP=PSIS/57.3
                COSISP=SI(DSISH)
                CFSISP=C*S(DSTCX)
55              VFL=VFWHIC-V46*CPSISH
                VP=VEWHIC-V46*CPDSISD
```

```
SUBROUTINE WINDC     74/74    OPT=1                    FTN 4.6+424    79/01/15.  03.01.01    PAGE  2

          VH=SQRT(VEX**2+VNW**2)
          PSIW=ATAN2(VEW,VNW)-PI
          CPSIW=COS(PSIW)
          SPSIW=SIN(PSIW)
          PSIREL=PSIW-PSISH
          CPSIREL=COS(PSIREL)
          SPSIREL=SIN(PSIREL)
    C     COMPUTE TURBULENCE EXTRAPOLATION BOUNDARIES
          YMAX=-RLTD*SPSIREL+BEAM/2.*CPSIREL
          YMAX1=YMAX-BEAM*CPSIREL
          YMIN=-BEAM/2.*CPSIREL+(RLS-RLTD)*SPSIREL
          YMIN1=YMIN
          XMIN1=-RLTD*CPSIREL-BEAM/2.*ABS(SPSIREL)
          XMIN2=(RLS-RLTD)*CPSIREL-BEAM/2.*ABS(SPSIREL)
          IF(YMIN.GT.-18.75) YMIN=-18.75
          IF(YMAX.LT.170.) YMAX=170.
          IF(PSIREL)50,49,50
   50     SLOPE1=(XMIN1-XMIN2)/(YMAX1-YMIN1)
   49     CONTINUE
          VW1=VW/76.
          VW1=VW/59.
    2     CONTINUE
  100     IF(TIME-TCOUNT)101,100,100
          TCOUNT=TCOUNT+DTW
          VETO=VETW
          VNTO=VNTW
    C     GUST MODEL EXTRAPOLATIONS FUNCTIONS
          XWIND=YE*SLSIW+XE*CPSIW
          YWIND=XE*CPSIW+YE*SPSIW
    C     XTAB,YTAB, ZTAB ARE INPUT TO TABLES
          XTAB=-XWIND
          YTAB=YWIND
          ZTAB=RLT-HTD
          FXI=1.
          FYI=1.
          FZI=1.
          IF(ZTAB.LT.0.) ZTAB=0.
          IF(ZTAB-44.95)31,31,30
   30     FZI=EXP((44.95-ZTAB)/BEAM)
   31     CONTINUE
          IF(ZTAB-GT.44.95)ZTAB=44.95
          IF(YTAB-YMAX)3,5,4
    4     FYI=EXP((YMAX-YTAB)/BEAM)
          GO TO 5
    3     IF(YTAB-YMIN)6,5,5
    6     FYI=EXP((YTAB-YMIN)/BEAM)
    5     CONTINUE
          IF(PSIREL)7,8,7
    8     XMIN=XMIN1
          GO TO 13
    7     IF(YTAB(-YMAX)9,10,10
   10     XMIN=XMIN1
          GO TO 13
    9     IF(YTAB-YMIN)11,12,12
   11     XMIN=XMIN2
          GO TO 13
```

```
SUBROUTINE WIND          74/74   OPT=1                FTN 4.3+424    74/01/15. 08.01.01    PAGE  3

115     112   YMIN=XMIN*SLOPE1*(Y*TN0-YMIN)
        113   CONTINUE
        14    IF(XTA4-XMIN)14,16,16
        14    EX1=EA((XTA4-XMIN)/REA4)
              GO TO 17
120     16    CONTINUE
        16    IF(XTA4-250.)17,17,1H
        1H    CONTINUE
        1H    EA1=1.-(XTA4-250.)*SLOPEX
              IF(EA1.LT.0.) EA1=0.
125     17    CONTINUE
        17    IF(XTA4.LT.0.) XTA4=0.
              IF(XTA4.GT.250.) XTA4=250.
              IF(YTA4.LT.-18.75)YTA4=-18.75
              IF(YTA4.GT.170.) YTA4=170.
130           F1=X1*FY1*67
        C           VXMS,VYMS,VZMS ARE MEAN VALUES
              VXMS=TA*1(XTA4,YTA4,7TA4,76.3)
              VYMS=TA*1(XTA4,YTA4,7TA4,79.3)
135           VZMS=TA*1(XTA4,YTA4,7TA4,82.3)
        C           SIGX,SIGY,SIGZ ARE VARIANCE VALUES
              SIGX=TA*1(XTA4,YTA4,7TA4,85.3)
              SIGY=TA*1(XTA4,YTA4,7TA4,88.3)
              SIGZ=T*91(XTA4,YTA4,7TA4,91.3)
              VX4A4=(VX4S-VMS)*F1
140           VY4A4=VY4S*F1
              VZ4A4=VZ4S*F1
              SIGX=SIGX*F1
              SIGY=SIGY*F1
              SIGZ=SIGZ*F1
145           BMODE=(TIME-BI)/2
        C        SPECIFY PERIODICITY OF RANDOM NUMBER CALL TO REGULATE FREQUENCY
        C        OF RANDOM TURBULENCE SIMULATION . INCREASE DTX,DTY,DTZ TO REDUCE
        C        FREQUENCY OF TURBULENCE.
        C        LINEARLY INTERPOLATE RANDOM NUMBER INPUT BETWEEN CALLS.
150     200   BANDX4=RANDX4
              TETTX=TCOUNTX+DTX
        200   IF(TIME-TCOUNTX)202,200,200
              CALL RAND(IRDSTX,IX,1.1,RANDX4)
              TCOUNTX=TCOUNTX+DTX
155     202   RANDX4=RANDX4+(R4NDX4-RA4)XO)*(TIME+DTX-TCOUNTX)/DTX
              IF(TIME-TCOUNTY)302,300,300
300           RANDY4=RANDY4
              CALL RAND(IRDSTY,IX,1.1,RANDY4)
              TCOUNTY=TCOUNTY+DTY
302           RANDY4=RANDY4+(R4NDY4-RANDY0)*(TIME+DTY-TCOUNTY)/DTY
160     400   RANDZ4=RANDZ4
              CALL RAND(IRDSTZ,IX,1.1,RANDZ4)
              TCOUNTZ=TCOUNTZ+DTZ
402           B4NDZ4=R4NDZ4-(R4DZ4-RANDZ0)*(TIME+DTZ-TCOUNTZ)/DTZ
165     C        TURBULENCE FREQUENCY VARIES WITH DOWNSTREAM RANGE
              OMEGAX=.17*Y*1
              OMEGAY=10.41*Y*1
              OMEGAZ=10.8*Y*1
              IF(XTA4-1.).500,500,501
170     500   OMEGAX=1.
              EOXE,XY=1.
```

```
SUBROUTINE WIND    74/74    OPT=1              FTN 4.7+428      79/01/15. 08.01.01      PAGE   4

              GO TO 504
        501   IF((TW--190.)532+503,503
        502   FOMEGX=1.-.004744*TAB
              FOMEGY=1.-.003766*TAB
              GO TO 504
        503   FOMEGX=.1935
              FOMEGY=.2842
        504   CONTINUE
    C         SCALE FILTER FREQUENCY WITH RANGE AND FREE STREAM VELOCITY
              OMEGX=OMEGX*FOMEGX
              OMEGY=OMEGY*FOMEGY
              OMEGZ=OMEGZ*FOMEGY
              EXPX=EXP(-DT*OMEGX)
              EXPY=EXP(-DT*OMEGY)
              EXPZ=EXP(-DT*OMEGZ)
    C         COMPUTED RANDOM TURBULENCE
              VXT=VXT*EXPX+(1.-EXPX)*4.48*SIGVX/SQRT(OMEGX)*RANDX*RMODE
              VYT=VYT*EXPY+(1.-EXPY)*4.48*SIGVY/SQRT(OMEGY)*RANDY*RMODE
              VZT=VZT*EXPZ+(1.-EXPZ)*4.48*SIGVZ/SQRT(OMEGZ)*RANDZ*RMODE
              VXTD=VXT
              VYTD=VYT
              VZTD=VZT
    C         TOTAL TURBULENCE IN WIND AXES
              VXTD=VX+VXD+VXT
              VYTD=VY-AD-VYT
              VZTD=VZ+AD+VZT
    C         TOTAL TURBULENCE IN INERTIAL AXES
              VXTH=VXTUR*COSIA-VYTUR*SINIA
              VETH=VYTUR*COSIA+VXTUR*SINIA
              VXTH=VZTUR
    101       CONTINUE
    102       IF(IRMODE.EC.-1) 102,103
              VETO=VXTH
              VETO=VYTH
              VETO=VZTH
    103       CONTINUE
    C         NEGATE VALUE OF TURBULENCE
              VXTUR=VXTD*TFACB*(VXTN-VXTO)
              VETUR=VYTD*TFACB*(VETN-VETO)
              VXTUR=VZTD*TFACB*(VDTN-VZTO)
              IF((IRMF.EQ.-1) PRINT 104,VXHS,VYHS,VZHS,SIGX,SIGY,SIGZ,FL,
            1 XTH,YTH,ZTH,SIGVEL,SLOPEL
    104       FORMAT(10X,12F10.4)
              RETURN
              END


    SYMBOLIC REFERENCE MAP (R=3)

    ENTRY POINTS    DEF LINE    REFERENCES
      1  WIND            1           23          214
```

SUBROUTINE WINDC 74/74 OPT=1 FTN 4.7+428 79/01/15. 03.01.01 PAGE 6

RELOCATION

VARIABLES SN TYPE

HLS	REAL		
RLTD	REAL		
RDDF	REAL		DEFINED 145 13
RX	REAL		
RXY	REAL		
RXZ	REAL		
SIGVX	REAL		
SIGVY	REAL		
SIGVZ	REAL		
SIGX	REAL		
SIGY	REAL		
SIG7	REAL		
SLOPEX	REAL		
SLOPEL	REAL		DEFINED 75 64
SPSIDEL	REAL		
SWSISA	REAL		
SPSTA	REAL		DEFINED 44 61
TCOUNT	REAL		33 153
TCOUNTX	REAL		34 158
TCOUNTZ	REAL		35 163
TFAC	REAL		208
TIME	REAL		155 159
VDTD	REAL		201
VDTD	REAL		
VDTIDH	REAL		
VFH	REAL		
VETD	REAL		200
VETIDH	REAL		
VFH	REAL		
VFH-TC	C-F		56
VATD	REAL		199
VATDH	REAL		
VHH	REAL		
VHH-TC	C-F		57
VS	REAL		54
VSI	REAL		77
VXBAR	REAL		
VXT	REAL		188
VXTD	REAL		
VX-S	REAL		
VY-AR	REAL		
VYT	REAL		189
VYTDH	REAL		
VY-S	REAL		
VZHAR	REAL		
VZT	REAL		190
VZTD	REAL		
VZTDH	REAL		
XS	REAL		

VARIABLES   SN TYPE   RELOCATION

721 XMIN	REAL	REFS	117	116	DEFINED	107	110	113	
723 XMIN1	REAL	REFS	75	107	110	DEFINED	70		
724 XMIN2	REAL	DEFS	75	113	115	DEFINED	71		
735 XTH?	REAL	REFS	117	118	121	123	126	127	132
			133	134	137	169	173		174
			213	175		126	127		
736 X?IND	REAL	REFS	47	DEFINED		89			
215 YE	REAL	C+F	REFS	7	85	66			
717 YMAX	REAL	REFS	67	73	100	101	109		
720 YMAX1	REAL	DEFINED	66	DEFINED	67				
721 YMIN	REAL	REFS	75	72	103	104	115		
722 YMIN1	REAL	DEFINED	61	DEFINED	69				
737 YTAH	REAL	REFS	75	72	103	112	128		129
			100	101	136	138	213		
			133	134					
735 YAIND	REAL	DEFINED	90	168	129				
721 ZTAH	REAL	REFS	90	107	115	DEFINED	99	133	134
740 ZTAH	REAL	REFS	137	130	213	DEFINED	91	95	99

FILE NAMES   MODE
OUTPUT   FMT   WRITES   213

EXTERNALS   TYPE   ARGS   LIBRARY   REFERENCES

ATAN2	REAL	2 LIBRARY	59					
COS	REAL	1 LIBRARY	60	55				
EXP	REAL	1 LIBRARY	101	97				
SQRD	REAL	5	157	152	118	184	186	
SIN	REAL	1 LIBRARY	61	62				
SQRT	REAL	1 LIBRARY	108	104	190			
TAN1	REAL	5	133	132	136	137	138	

INLINE FUNCTIONS   TYPE   ARGS
TANS   REAL   1 INTRIN   DEF LINE REFERENCES
                                    71   70   71

STATEMENT LABELS

		DEF LINE	REFERENCES	
1		65	2924	
121 2		79	24	
100 3	INACTIVE	103	100	
0 4		101	100	
173 5		105	100	102 2*103
0 6	INACTIVE	104	103	
176 7		105	2*104	
0 8		107	106	
202 9	INACTIVE	112	106	
0 10		110	2*100	
0 11	INACTIVE	113	112	
206 12		115	2*112	
212 13	INACTIVE	116	104	
0 14		117	117	111 114
0 15	INACTIVE	20	2*104	
217 16		120	2*117	
226 17	INACTIVE	105	114	2*121
0 18		122	121	
6 20		26	11	
27 21		43	30	

ROUTINE NAME   74/74   OPT=1   FTN 4.7+463   79/01/15. 08.01.01   PAGE   8

STATEMENT LABELS
        DEF LINE   REFERENCES

       0 30   INACTIVE   67   45
     155 31   96   2895
     117 47   INACTIVE   75   74
       0 50   INACTIVE   75   2874
       0 100   INACTIVE   81   2660
       0 101   202   40
       0 102   INACTIVE   254   203
     454 103   207   203
     617 104   FMT   215   213
       0 200   INACTIVE   151   20160
     302 202   INACTIVE   154   150
       0 300   INACTIVE   156   20166
     315 302   INACTIVE   159   155
       0 400   INACTIVE   161   20160
     332 402   INACTIVE   164   160
       0 500   INACTIVE   170   20160
     302 501   INACTIVE   173   169
       0 502   INACTIVE   174   173
     351 503   177   20173
     304 504   176   172   176

COMMON BLOCKS   LENGTH   MEMBERS - BIAS NAME(LENGTH)
        A   500   0 A   (500)
        XFLOAT   500
        IFIXED   200   0 IA   (200)
        C-F   200   0 IH   (200)
        IC-F   50   0 IM   (50)

EQUIV CLASSES   LENGTH   MEMBERS - BIAS NAME(LENGTH)
        A   500   75 VXW   (1)   76 VEW   (1)   77 VDW   (1)
                             82 ALT   (1)   167 DT   (1)   302 TIME   (1)
                            418 VNTURB (1)   419 VETURB (1)   420 VDTURB (1)
                            499 IVORF (1)
        IA   200   0 IVORF (1)
        T   200   24 V5   (1)   34 VNWBIC (1)   35 VFWBIC (1)
                             83 PSIS   (1)   102 HTD   (1)   140 XE   (1)
        IA   50   141 YE   (1)
        IH   16 IURCE   (1)   19 IWIND (1)

STATISTICS
        PROGRAM LENGTH   10052   517
        CH LABELED COMMON LENGTH   16462   450

PITCH TIME HISTORY FOUR 3? AV-8A

STEADY WHIRDLE VERSUS RANGE

STEADY WHIRDLE VS RANGE

DOWN WASH WITH ILMORH=1

SIGMA REGION RIDDLE

TAU RANDOM RIDDLE

DCL 120 G. TAUR MOD + ESTIMATE

STABILIZER VS TIME THROUGH

STICK VS STABILIZER GRADING

A P P E N D I X   E

Variable Definitions for FF 1052 Program

A	Common Array
ALT	Altitude of Aircraft cg Above Sea Level – Ft.
B	Common Array
Beam	Ship Beam – Ft.
CPSIREL	Cosine of Relative Wind Angle
CPSISR	Cosine of Ship Heading Angle
CPSIW	Cosine of Absolute Wind Direction
DT	Integration Frame Time – Sec.
DTW	Integration Frame Time of Turbulence Subroutine – Sec.
DTX	Update Time Increment of X-Random Number Generator – Sec.
DTY	Update Time Increment of Y Component Random Number Generator
DTZ	Update Increment of Z Component Random Number Generator
EXPX	X Component Difference Equation Parameter
EXPY	Y Component Difference Equation Parameter
EXPZ	Z Component Difference Equation Parameter
FOMEGX	X Frequency Extrapolation Function
FOMEGY	Y Frequency Extrapolation Function
FX1	X Direction Extrapolation Function
FY1	Y Direction Extrapolation Function
FZ1	Z Direction Extrapolation Function
F1	Total Extrapolation Function
HTD	Height of Touchdown Point Above Sea Level – Ft.
IA	Integer Common Array
IB	Integer Common Array
IMODE	Simulation Mode Switch
IONCE	Random Number Startup Option Switch
IRDSTX	Initial Value of X – Random Number Sequence
IRDSTXI	Current Value of X – Random Number Sequence
IRDSTY	Initial Value of Y – Random Number Sequence
IRDSTYI	Current Value of Y – Random Number Sequence
IRDSTZ	Initial Value of Z – Random Number Sequence

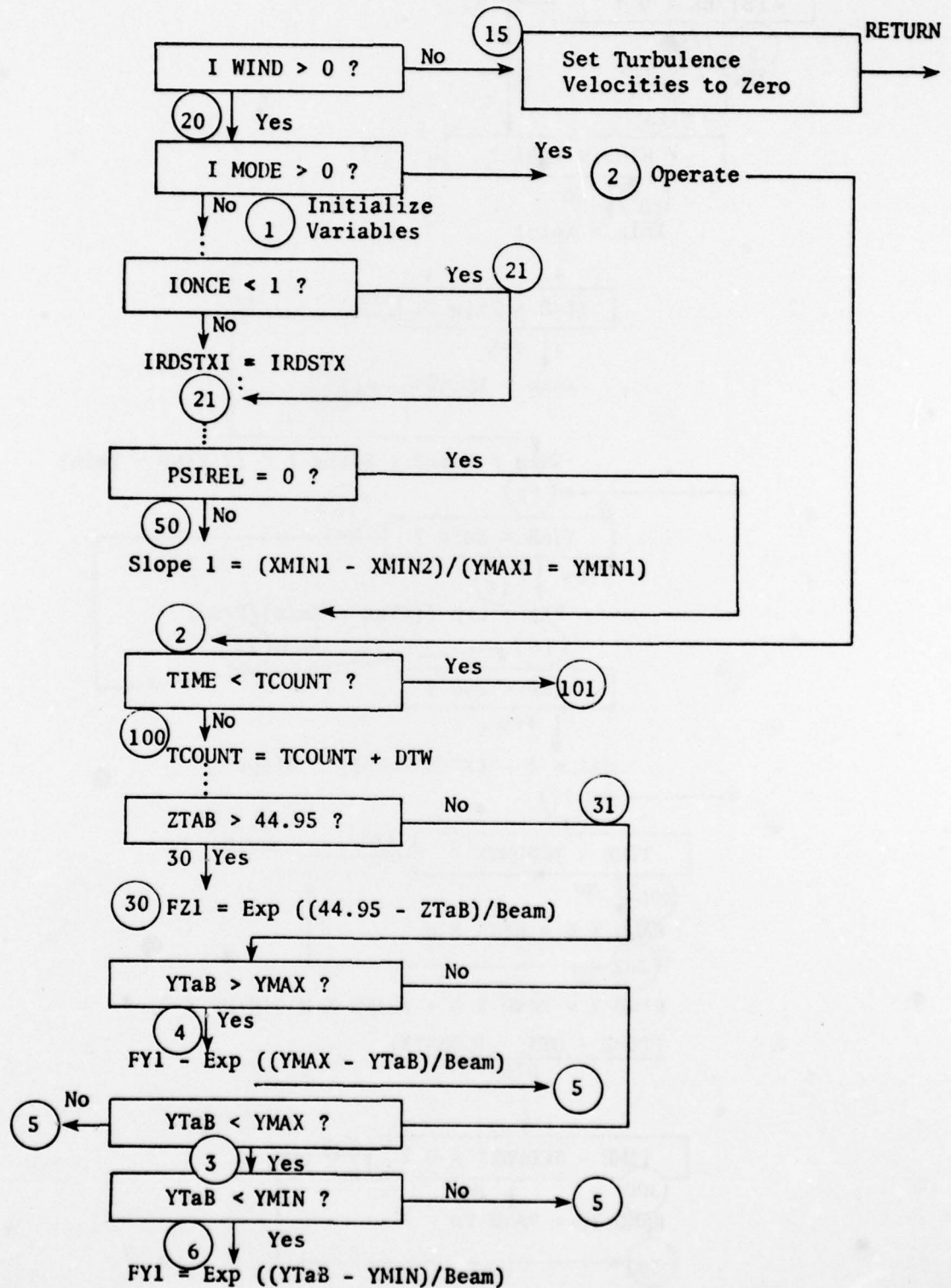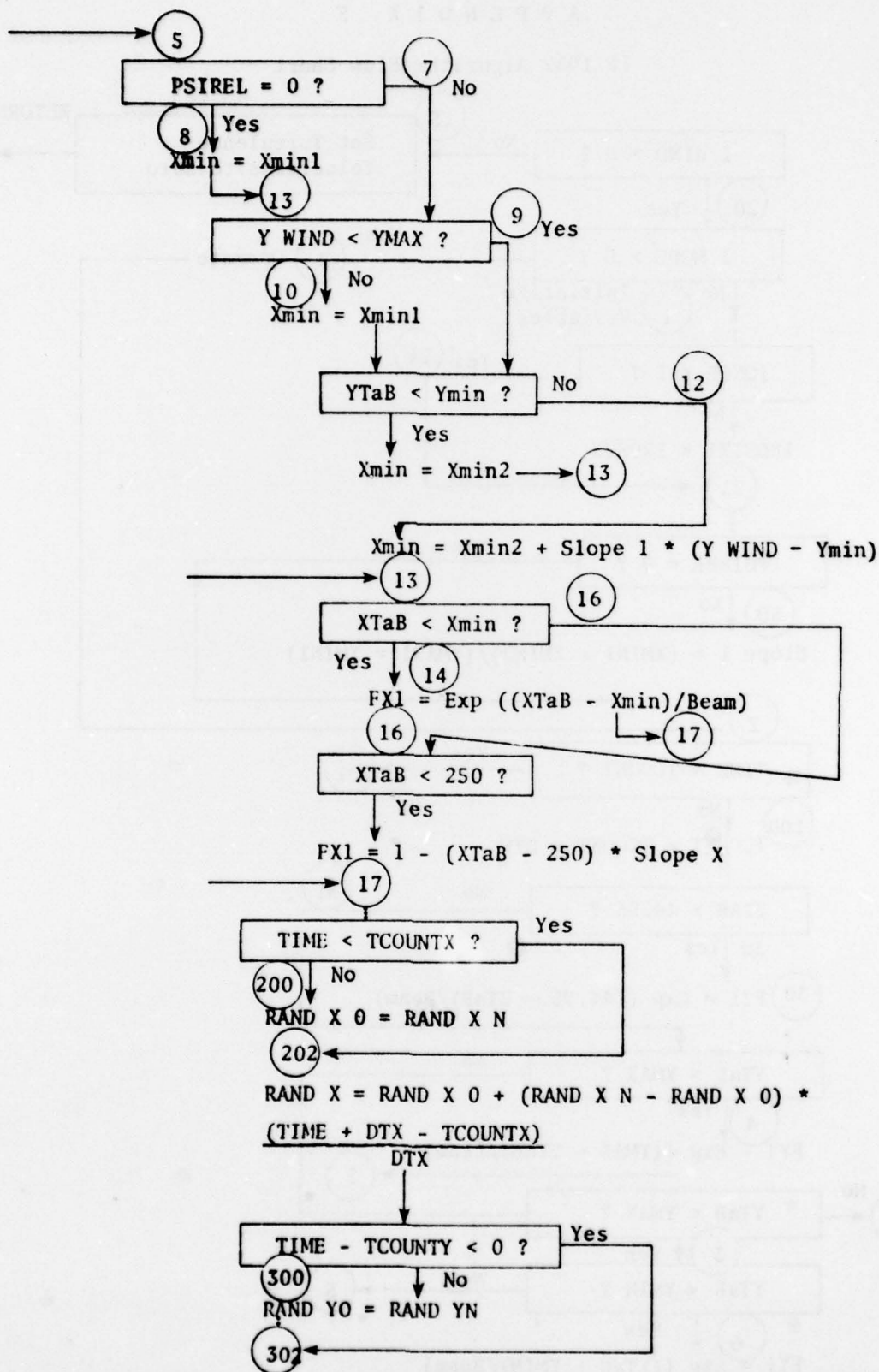| IRDSTZI	Current Value of Z - Random Number Sequence
IWIND	Turbulence on/off Flag
IX	Machine Dependent Random Number Generator Parameter
OMEGX	X - Component Filter Constant
OMEGY	Y - Component Filter Constant
OMEGZ	Z - Component Filter Constant
PI	3.14159
PSIREL	Angle of Relative Wind With Respect to Ship - Rad.
PSIS	Ship Heading - Deg.
PSISR	Ship Heading - Rad.
PSIW	Absolute Wind Direction - Rad.
RANDX	Interpolated Value of X - Component Random Number Generator
RANDXN	Current Output of X - Random Number Generator
RANDXO	Previous Output of Y - Component Random Number Generator
RANDY	Interpolated Value of Y Component Random Number Generator
RANDYN	Current Output of Y Random Number Generator
RANDYO	Previous Output of Y Random Number Generator
RANDZ	Interpolated Value of Z Component Random Number Generator
RANDZN	Current Output of Z Random Number Generator
RANDZO	Previous Output of Z Random Number Generator
RLS	Ship Length - Ft.
RLTD	Distance From Bow to Touchdown Point - Ft.
RMODE	Mode Parameter
RNX	X Component Time Increment Ratio
RNY	Y Component Time Increment Ratio
RNZ	Z Component Time Increment Ratio
SIGVX	X Velocity Variance - Ft./Sec.
SIGVY	Y Velocity Variance - Ft./Sec.
SIGVZ	Z Velocity Variance - Ft./Sec.
SIGX	Tabulated X Component Variance - Ft./Sec.
SIGY	Tabulated Y Component Variance - Ft./Sec.
SIGZ	Tabulated Z Component Variance - Ft./Sec.
SLOPEX	X Extrapolation Parameter
SLOPE1	X Boundary Definition Parameter
SPSIREL	Sine of Relative Heading Angle
SPSISR	Sine of Ship Heading

SPSIW	Sine of Wind Heading
TCOUNT	Update Time Counter - Sec.
TCOUNTX	X Update Time - Sec.
TCOUNTY	Y Update Time - Sec.
TCOUNTZ	Z Update Time - Sec.
TFAC	Turbulence Update Paramater
TIME	Simulation Time - Sec.
VDTN	Current Value of Vertical Turbulence Component - Ft./Sec.
VDTO	Previous Value of Vertical Turbulence Component - Ft./Sec.
VDTURB	Interpolated Value of Vertical Turbulence - Ft./Sec.
VDW	Total Vertical Wind Including Free Air Wind - Ft./Sec.
VETN	Current Value of Computed East Turbulence Component - Ft./Sec.
VETO	Previous Value of Vertical Turbulence Component - Ft./Sec.
VETURB	Interpolated Value of East Turbulence - Ft./Sec.
VEW	Total East Wind - Ft./Sec.
VEWBIC	Initial East Wind Component - Ft./Sec.
VNTN	Current North Turbulence Update - Ft./Sec.
VNTO	Previous North Turbulence Update - Ft./Sec.
VNTURB	Interpolated North Turbulence Component - Ft./Sec.
VNW	North Wind Component - Ft./Sec.
VNWBIC	Initial North Wind Component - Ft./Sec.
VS	Ship Speed - Ft./Sec.
VW	Total Steady Wind - Ft./Sec.
VW1	Velocity Ratio
VXBar	Mean X Turbulence Velocity - Ft./Sec.
VXT	Random X Component of Turbulence - Ft./Sec.
VXTP	Previous Value of VXT - Ft./Sec.
VXTURB	Total X Component of Turbulence - Ft./Sec.
VXWS	Tabulated Mean X Velocity Component - Ft./Sec.
VYBar	Mean Y Turbulence Velocity - Ft./Sec.
VYT	Random Y Component of Turbulence - Ft./Sec.
VYTP	Previous Value of VYT - Ft./Sec.
VYTURB	Total Y Component of Turbulence - Ft./Sec.
VYWS	Tabulated Mean Y Velocity Component - Ft./Sec.
VZBar	Z Component Mean Turbulence Velocity - Ft./Sec.
VZT	Z Component of Random Turbulence - Ft./Sec.
VZTP	Previous Value of VZT - Ft./Sec.

E - 3

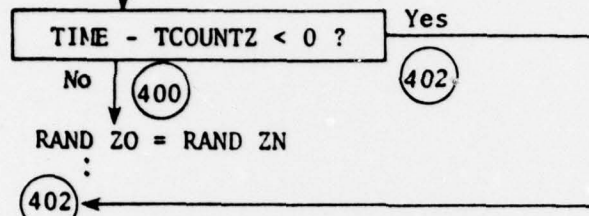| VZTURB	Total Z Component of Turbulence - Ft./Sec.
VZWS	Tabulated Mean Z Turbulence Velocity - Ft./Sec.
XE	North - South Distance From Aircraft cg to Touchdown Pt. - Ft.
XMIN	Forward Limit on Turbulence Region - Ft.
XMIN1	Intermediate Value of XMIN - Ft.
XMIN2	Intermediate Value of XMIN - Ft.
XTaB	X Table Lookup Parameter - Ft.
XWIND	Aircraft Position Measured Parallel to Relative Wind - Ft.
YE	Aircraft East - West Position Relative to Touchdown Point - Ft.
YMAX	Right Limit on Turbulence - Ft.
YMAX1	Intermediate Value of YMAX - Ft.
YMIN	Left Limit on Turbulence - Ft.
YMIN1	Intermediate Value of YMIN - Ft.
YTaB	Y Table Lookup Parameter
YWIND	Aircraft Position Relative to Touchdown Point Measured Transverse to Wind Direction - Ft.
ZTaB	Z Table Lookup Parameter - Ft.

A P P E N D I X   F

FF 1052 Algorithm Flow Chart

PSIREL = 0 ? — 7, No

8, Yes
Xmin = Xmin1
13

9, Yes
Y WIND < YMAX ?

10, No
Xmin = Xmin1

YTaB < Ymin ? — No, 12

Yes

$Xmin = Xmin2$ → 13

$Xmin = Xmin2 + Slope\ 1 * (Y\ WIND - Ymin)$

13

XTaB < Xmin ? — 16

Yes, 14
$FX1 = Exp\ ((XTaB - Xmin)/Beam)$

16 → 17

XTaB < 250 ?

Yes

$FX1 = 1 - (XTaB - 250) * Slope\ X$

17

TIME < TCOUNTX ? — Yes

200, No
RAND X 0 = RAND X N

202

$RAND\ X = RAND\ X\ 0 + (RAND\ X\ N - RAND\ X\ 0) * \dfrac{(TIME + DTX - TCOUNTX)}{DTX}$

TIME - TCOUNTY < 0 ? — Yes

300, No
RAND YO = RAND YN

302

F - 2

RAND Y = RAND YO + (RAND YN - RAND YO) * (TIME + DTY - TCOUNTY)/DTY

TIME - TCOUNTZ < 0 ? Yes

No (400) (402)

RAND ZO = RAND ZN
$\vdots$

(402)

RAND ZN = RAND ZO + (RAND ZN - RAND ZO) * (TIME + DTZ - TCOUNTZ)/DTZ

XTaB $\leq$ 18 ? No

Yes 500

FOMEGX = 1.0
·

(504) (501)

XTaB < 190 ? No

(502) Yes

FOMEGX = 1 - .0042777 * XTaB

(503) (504)

FOMEGX = .1935

(504) (101) No

IMODE = -1 ?

Yes

VNTO = VNTN
$\vdots$

(103)

TFAC = (TIME + DTW - TCOUNT)/DTW

$\vdots$

Return
End

F - 3
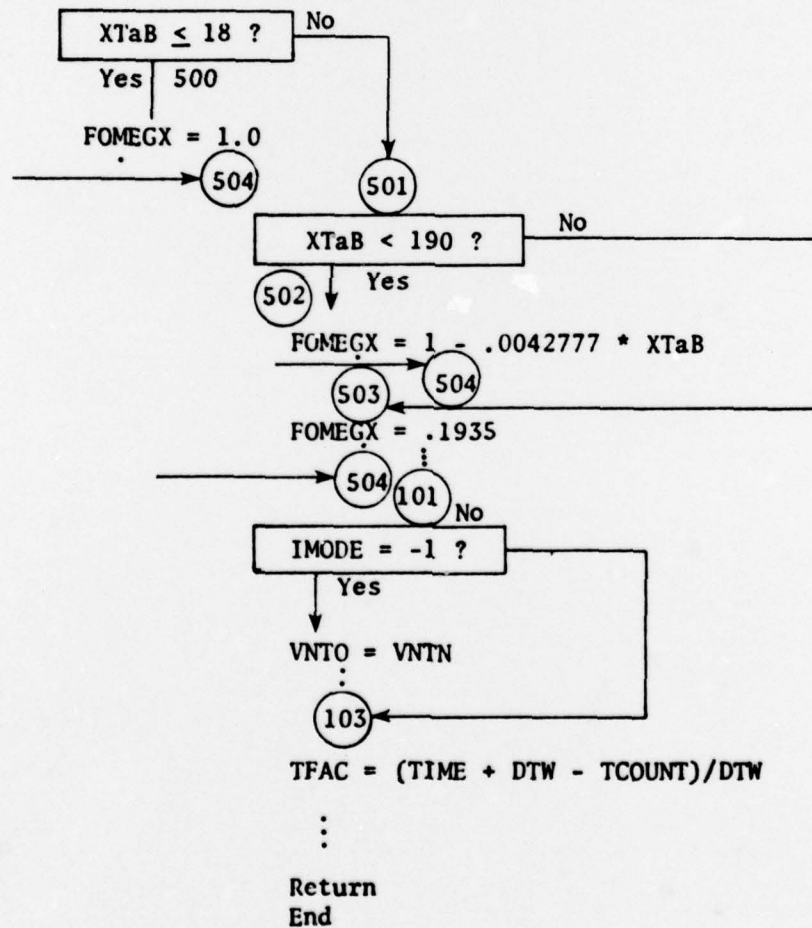
DISTRIBUTION LIST (Continued)

DISTRIBUTION LIST

REPORT NO. NADC-78182-60

AIRTASK NO. WF-41-400-000

P.E. No. 62241N

	No. of Copies
NAVAIR (AIR-950D...	8
(2 for retention)	
(3 for AIR-320D)	
(3 for AIR-530112)	
DDC	12
NAVAIRTESTCEN, Patuxent River, Md. 20970	1
(1 for Mr. Anthony Rosetti)	
NASA Ames Research Center, Moffet Field, CA 94035	1
(1 for Mr. Walter McNeill)	
Boeing Vertol Company, P.O. Box 16858, Phila., PA 19142	1
(1 for Mr. Theodore Garnett, Jr.)	
McDonnell Aircraft Company, St. Louis, MO 63166	1
(1 for Mr. Douglas Miller, Harrier Project)	
Vought Corporation, P.O. Box 5907, Dallas, TX 75222	2
(1 for Mr. Robert Fortenbaugh)	
(1 for Dr. Julian Wolkowitch)	
Systems Control Incorporated, 1801 Page Mill Road,	
Palo Alto, CA 94304	1
(1 for Mr. Jeffrey Bohn)	
Rockwell International, Columbus, OH 43216	1
General Dynamics Corporation, Ft. Worth, TX 76101,	
P. O. Box 748	1
Northrup Corporation, Hawthorne, CA 90250	1
Grumman Aerospace Corp., Beth Page, L.I., NY 11714	2
(1 for Mr. S. Kalemaris)	
(1 for Mr. P. Martorella)	
Royal Aeronautical Establishment, Bedford, England	2
(1 for Mr. A. Woodfield)	
(1 for Mr. B. N. Tomlinson)	
Systems Technology, Inc., 13766 Hawthorne Blvd., Hawthorne,	
CA 90250	1
Bell Helicopter Company, Fort Worth, TX 76101	1
(1 for Mr. Peter O'Reilly)	
NAVEDTRA SUPP CENLANT, Bldg 286, Naval Station,	
Norfolk, VA 23511	1
(1 for Mr. Brian Sonberg)	
Lockheed California, Company 75-84/63/A-1, Burbank,	
CA 91520	1
(1 for Mr. Arthur Schuetz)	
National Research Council Canada, Ottawa, Canada	1
(1 for Dr. Maxwell Sinclair)	